

Naval Research Laboratory

Washington, DC 20375-5320



NRL/FR/6180--97-9861

Virtual Environment Firefighting/Ship Familiarization Feasibility Tests

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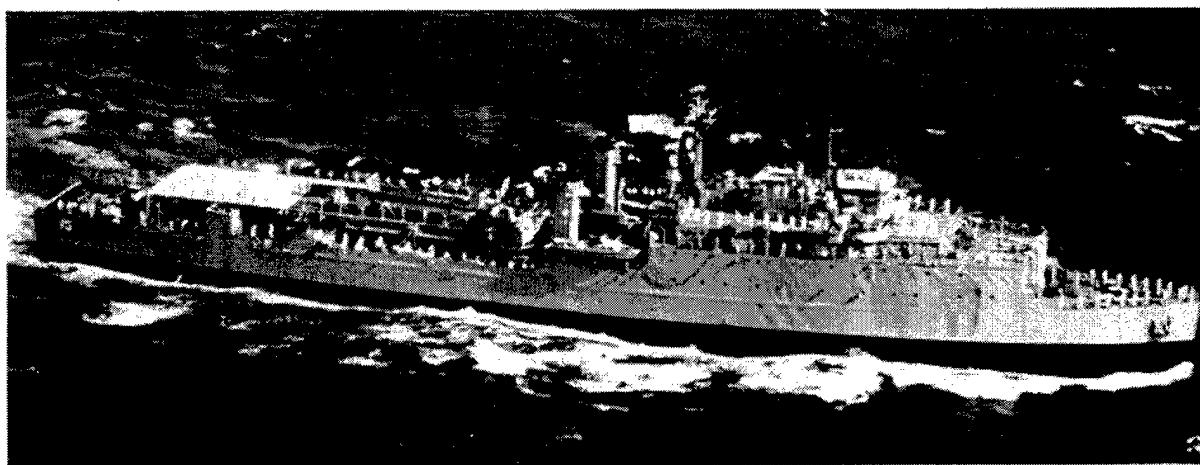
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September 30, 1997

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19971208 051

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget: Paperwork Reduction Project (0704-0188), Washington, DC 20503.</p>			
1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED	
	September 30, 1997	Interim; Tests conducted 18-22 September 1995	
4. TITLE AND SUBTITLE			5. FUNDING NUMBERS
Virtual Environment Firefighting/Ship Familiarization Feasibility Tests			PE - 64516 PR - S2054
6. AUTHOR(S)			
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)			8. PERFORMING ORGANIZATION REPORT NUMBER
Naval Research Laboratory Washington, DC 20375-5320			NRL/FR/6180--97-9861
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER
Chief of Naval Operations, Washington, DC 20350 Naval Sea Systems Command, Arlington, VA 22242			
11. SUPPLEMENTARY NOTES			
<p>*Information Technology Division **Naval Computer and Telecommunication Station/DC †Navy Personnel Research & Development Center, San Diego, CA ‡Hughes Associates, Inc., Baltimore, MD §Consultant</p>			
12a. DISTRIBUTION/AVAILABILITY STATEMENT		12b. DISTRIBUTION CODE	
Approved for public release; distribution unlimited.			
13. ABSTRACT (Maximum 200 words)			
<p>Virtual Environments Firefighting/Ship Familiarization Feasibility Tests were conducted on the ex-USS <i>Shadwell</i>. The results of these tests indicate that there are measurable gains using virtual environment (VR) training with respect to water usage and time to achieve complete extinguishment. The data also indicates gains for the time to travel from Repair 2 to the fire compartment and begin the initial attack. The time to transit from the 01 level to the fire area under reduced visibility was reduced by one-half for subjects trained with VR.</p>			
14. SUBJECT TERMS			15. NUMBER OF PAGES
ex-USS <i>Shadwell</i> Training			53
Firefighting Virtual environment			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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VIRTUAL ENVIRONMENT FIREFIGHTING/SHIP FAMILIARIZATION FEASIBILITY TESTS

1.0 INTRODUCTION

The Navy Technology Center For Safety and Survivability at the Naval Research Laboratory (NRL) is assisting in developing a virtual environments (VE) system to be used as a tool for shipboard firefighter training and mission rehearsal. Virtual environment is a term used to describe a computer-generated, three-dimensional simulation of real-world conditions in which the VE user is able to interactively participate. The system being developed by NRL is referred to as "immersive VE" because it incorporates a special head-mounted display (HMD) that is worn by the user. The HMD allows the user to see only the virtual world in which he or she is "immersed." Through appropriate programming, modeling, and simulating, the user is given a sense of actually being "in" the simulated world created by the computer.

The initial objective of this R&D effort was to develop a system that could demonstrate the potential use of VE for ship familiarization and for training shipboard firefighters. Previous research [1] has shown that visibility and familiarization with the compartments near a fire are two factors that can have a significant impact on the ability of a firefighting team to extinguish the fire. VE systems provide a flexible synthetic environment in which firefighters can familiarize themselves with an unfamiliar part of the ship. VE systems also allow firefighters to practice tactics, strategies, and procedures by interacting with simulated fire and smoke without risking lives or property.

A series of tests designed to evaluate the feasibility of using VE for firefighter training were conducted on board the ex-USS *Shadwell*, the Navy's full-scale damage control R&D platform [2]. These tests were conducted during the week 18-22 September 1995. The tests were conducted in two phases. Phase I was a navigation task that evaluated the effectiveness of VE for shipboard-familiarization training in reduced visibility. This was accomplished by having the test participants travel a specified path through the ship in a simulated smoke-filled environment. Phase II was a live-firefighting evolution that required the test participant to function as the team leader. The team leader directed the fire party to locate and retrieve specific firefighting equipment, perform standard firefighting procedures, and lead the fire party to extinguish the fire. The principle measures of performance for both phases of testing were the speed and accuracy with which the task was performed.

2.0 OBJECTIVE

The feasibility test comprised two phases. Phase I was a navigation task in which the participant's task was to traverse a specified path through the *Shadwell* while wearing a firefighter's mask with a special faceplate that simulates a smoke-filled environment. Phase I required the traversal of three decks, four doors, three passageways, two inclined ladders, and one compartment, with eight possible wrong turns, to achieve the single goal of covering an approximate distance of 24 m (80 ft). Phase II required the participant to locate and retrieve specific firefighting equipment and lead the firefighting team to extinguish

a real shipboard fire. Phase II required traversal of two decks, two passageways, one inclined ladder, three compartments, four doors, with nine possible wrong turns, to achieve three goals, for an approximate distance of 21 m (70 ft).

Twelve enlisted personnel participated—eight men and four women from two ships, the USS *Inchon* (MCS-12) and the USS *Puget Sound* (AD-38). All firefighters were either fire-team or team-leader qualified. None of the participants was familiar with the *Shadwell*. The test participants were divided into a traditional training group and a VE training group with the two groups having the same number of males and females. Both groups were given mission briefings to inform them of their assigned task, followed by time to plan their mission using a written mission statement and ship's drawings. The traditional training group then performed their tasks aboard the *Shadwell*, and performance measurements were taken and evaluated.

After their mission briefing and mission planning time, the VE training group used VE to familiarize themselves with the layout of the ship and to rehearse their assigned tasks, with and without simulated smoke and fire. After completion of their training, the VE training group then performed their tasks aboard the *Shadwell*, and performance measurements were taken and evaluated. The performance measurements that were collected during both phases of the tests were (1) time to complete the task and (2) number of wrong turns taken while performing the task.

3.0 SHIP FAMILIARIZATION FEASIBILITY IN VIRTUAL ENVIRONMENT

In the navigation task, participants traversed a specified path through the *Shadwell* in a simulated smoke-filled environment. This test was designed to evaluate the effectiveness of VE for shipboard-familiarization training in reduced visibility. No firefighting skills were involved in this task, so variability in training and experience at fighting fires among test participants was not a factor. Data collected for Phase I include the time taken to accomplish the task and the number of wrong turns taken during the test. The compartments of the *Shadwell* used for Phases I and II contained no overlapping areas so that familiarization gained in the Phase I test run could not be transferred to Phase II.

Only trained Navy firefighters were considered in selecting participants for this test. The Navy has unique requirements, tactics, and training for firefighters, and since Navy personnel are the intended users of this type of VE training, it was important to have potential users as the test participants. Twelve enlisted personnel participated, eight men from the USS *Inchon* and four women from the USS *Puget Sound*. Some participants were team-leader qualified but most were only team qualified. None of the participants was familiar with the *Shadwell*.

The test participants were divided into a traditional training group and a VE training group. To prevent gender bias in the test results, the males and females were divided equally between the two groups. In order to establish how the two groups differed, background information was collected, questionnaires were completed, and cognitive tests were given. An Immersive Tendencies Questionnaire [3] was used to measure a participant's tendency to become immersed in various types of captivating activities. The cognitive tests were a map-planning test and a paper-folding test. The map-planning test measured the speed at which a participant can scan a visually complicated spatial field. This test should help explain any differences in the participants' ability to effectively use damage control (DC) diagrams (i.e., DC plates). The paper-folding test determined visualization skills, specifically the ability to manipulate or transform a spatial pattern into other arrangements. This ability is related to general spatial ability and might correlate with a participant's navigation performance. After completing the VE training for Phase I, the VE training group was also given a Simulator Sickness Questionnaire [4] to assess the participant's tendency to become ill from using the VE equipment, and a Presence Questionnaire [3] to assess their ability to relate their

actions in VE to real-world experiences. When performing the test runs for both phases, traditional training and VE training group participants alternated turns.

To familiarize the VE test group with the VE equipment and user interface in the simulated world, a practice session was conducted prior to official testing. The practice session was conducted in a group to guarantee that all participants were given the same information. This session used a model that contained decks, walls, doors, hatches, inclined ladders, lockers, safety chains, and fire hoses that resembled those in the *Shadwell* model, but the physical layout of the practice model did not resemble any portion of the *Shadwell*. Participants were required to navigate through the practice model while descending and ascending ladders, opening and closing doors, and avoiding obstacles, just as they would be required to do for the test. Participants were allowed to practice until they felt comfortable with the VE controls and displays.

The equipment used for the virtual environment includes a Silicon Graphics dual-R4400, 200 MHz Onyx with Reality Engine (RE2) Graphics and two raster managers, a Polhemus Fastrak tracker with two channels of six degrees-of-freedom (6 DOF) electromagnetic tracking, a Virtual Research VR4 HMD, and a custom-made six DOF joystick pointer device.

3.1 Test Procedure

For Phase I, the test procedure began with a mission review presentation by the test director who defined the task and described the route to be used. The mission review for this phase was presented to all participants as a group, but they completed the navigation test individually. Participants were instructed to maintain existing door closures (which is standard procedure under certain conditions on ships) but that they would be given assistance opening and closing doors if needed. They were told if they turned the wrong way, the only correction they would receive is being told "wrong way." The starting point was the water-tight door WTD 01-29-1 on the Superstructure (01) Deck, and the destination was a porthole in compartment 2-23-3-L. The participants were told they would be timed from when they opened the first door until they touched the porthole. They were instructed to move through the course as quickly as possible, making as few mistakes as possible. Figures 1, 2, and 3 show the plan view diagrams used during the mission review. The heavy dotted line (which was not on the original diagram) shows the path taken during the test. The Phase I "start" position is indicated on Fig. 1, and the "porthole" position is shown on Fig. 3. The test began on the Superstructure Deck and went to the starboard side and down an inclined ladder to the Main Deck. Participants then located and descended the second inclined ladder to the Second Deck where they found the designated compartment containing the porthole. Phase I required the traversal of three decks, four doors, three passageways, two inclined ladders, and one compartment, with eight possible wrong turns, to achieve a single goal (touch the porthole), covering an approximate distance of 24 m (80 ft).

Prior to an individual's turn to take the test, they were given 5 min for mission rehearsal where they could study the DC plates and a written mission statement. DC plates are a collection of isometric views of a ship, which taken together, detail the ship's systems. The DC plates used for this test show only the structural layout of the ship. Figures 4, 5, and 6 are copies of portions of the DC plates that show the test area. Figure 7 shows the mission statement used for Phase I.

After completing their mission rehearsal, the traditional training group proceeded to take the Phase I test. The VE training group proceeded to the VE rehearsal prior to taking the test.

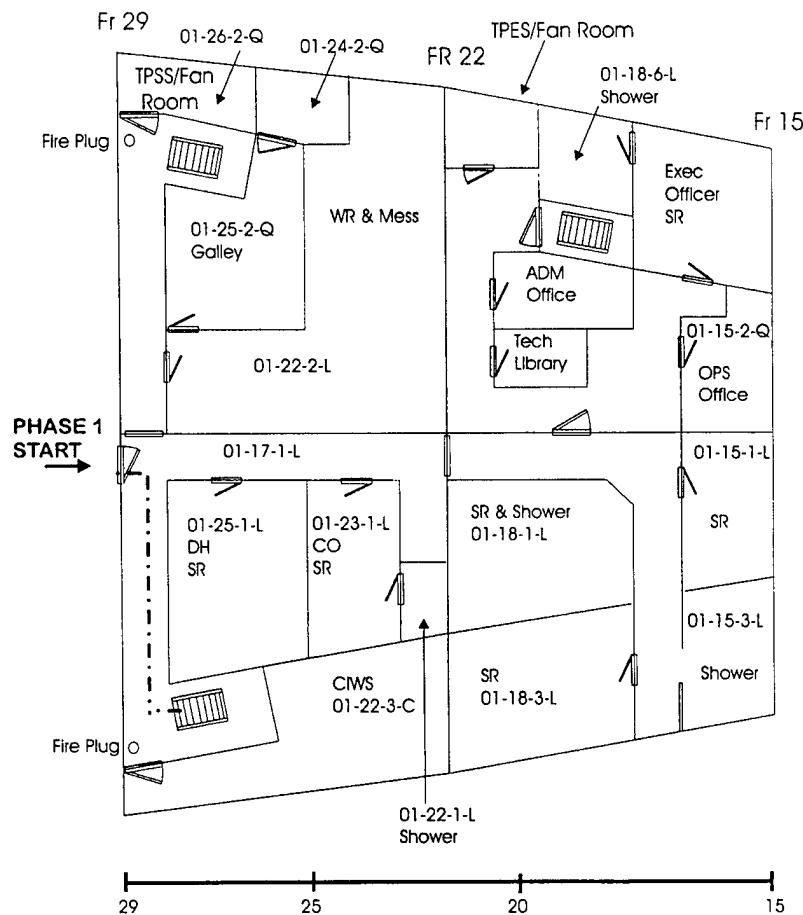
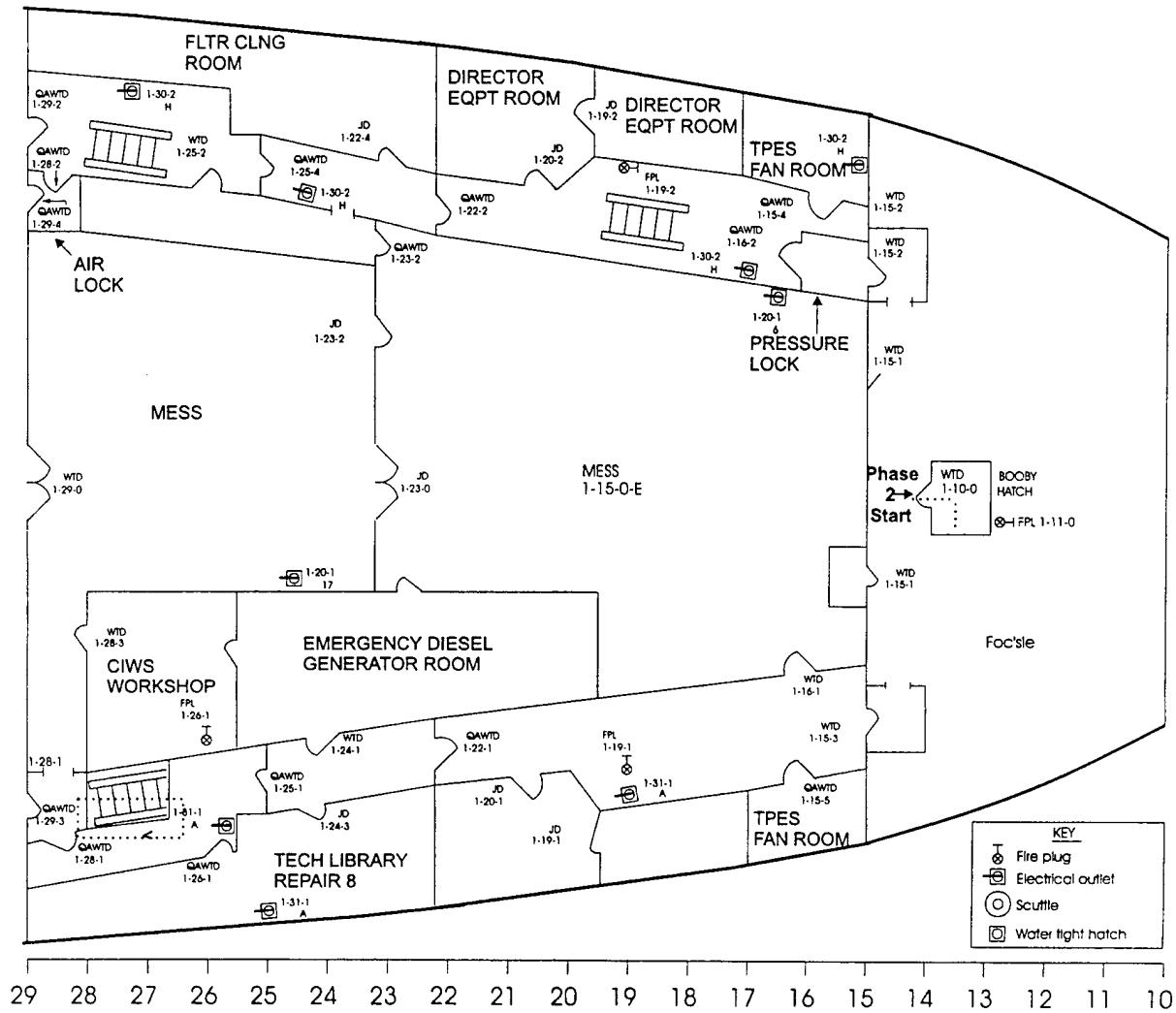


Fig. 1 — Plan view diagram of superstructure (01) deck



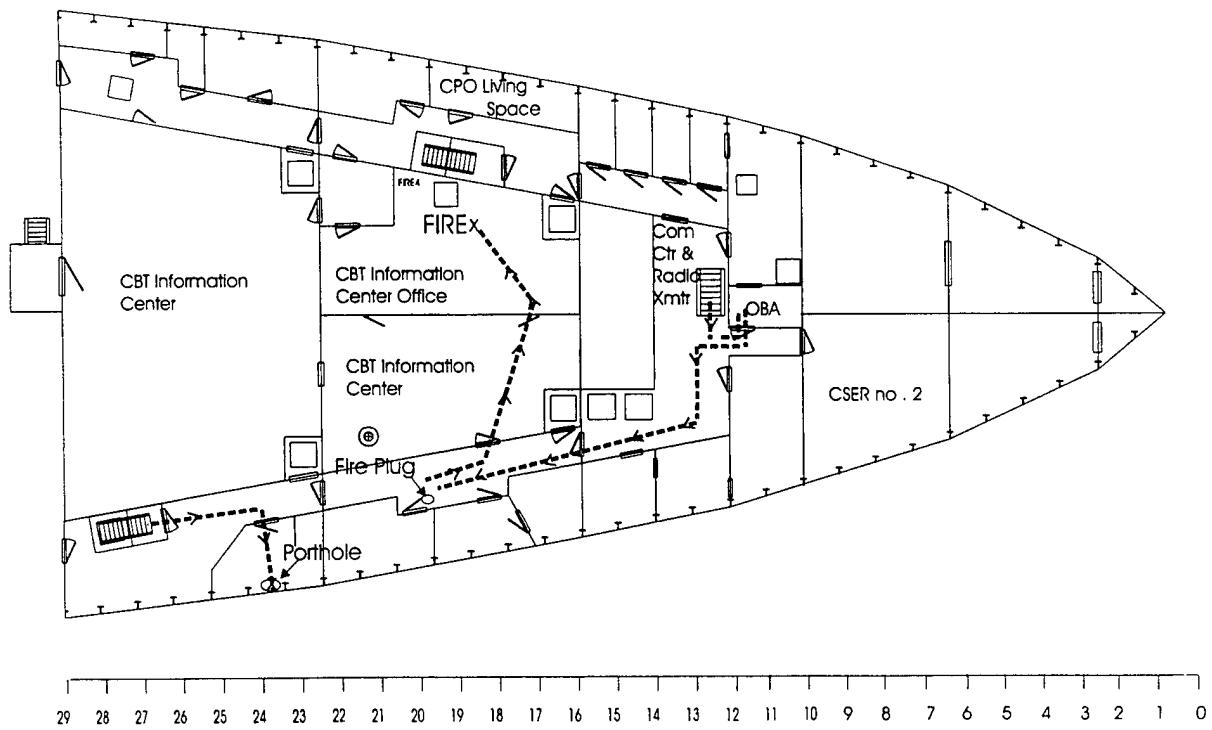


Fig. 3 — Plan view diagram of Second Deck

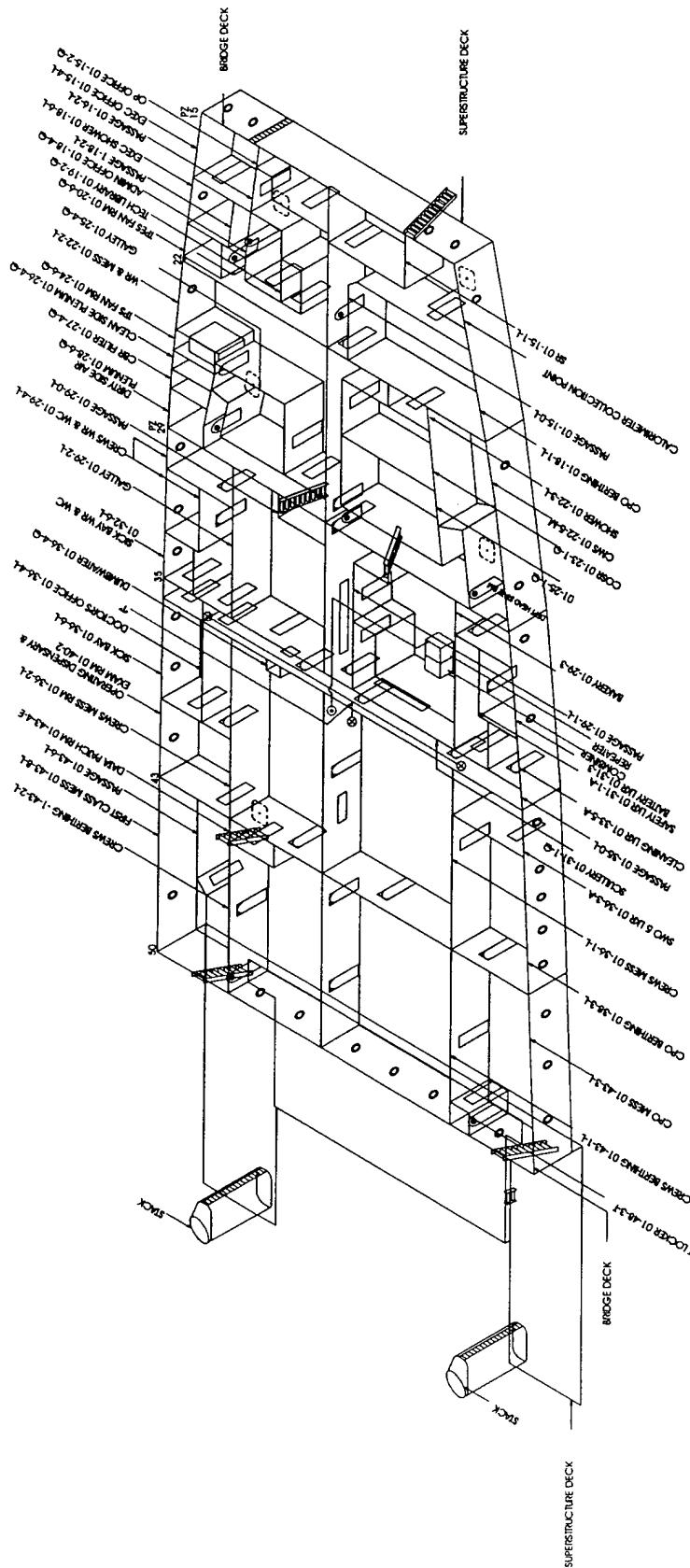


Fig. 4 — Portion of DC plates showing superstructure (01) deck

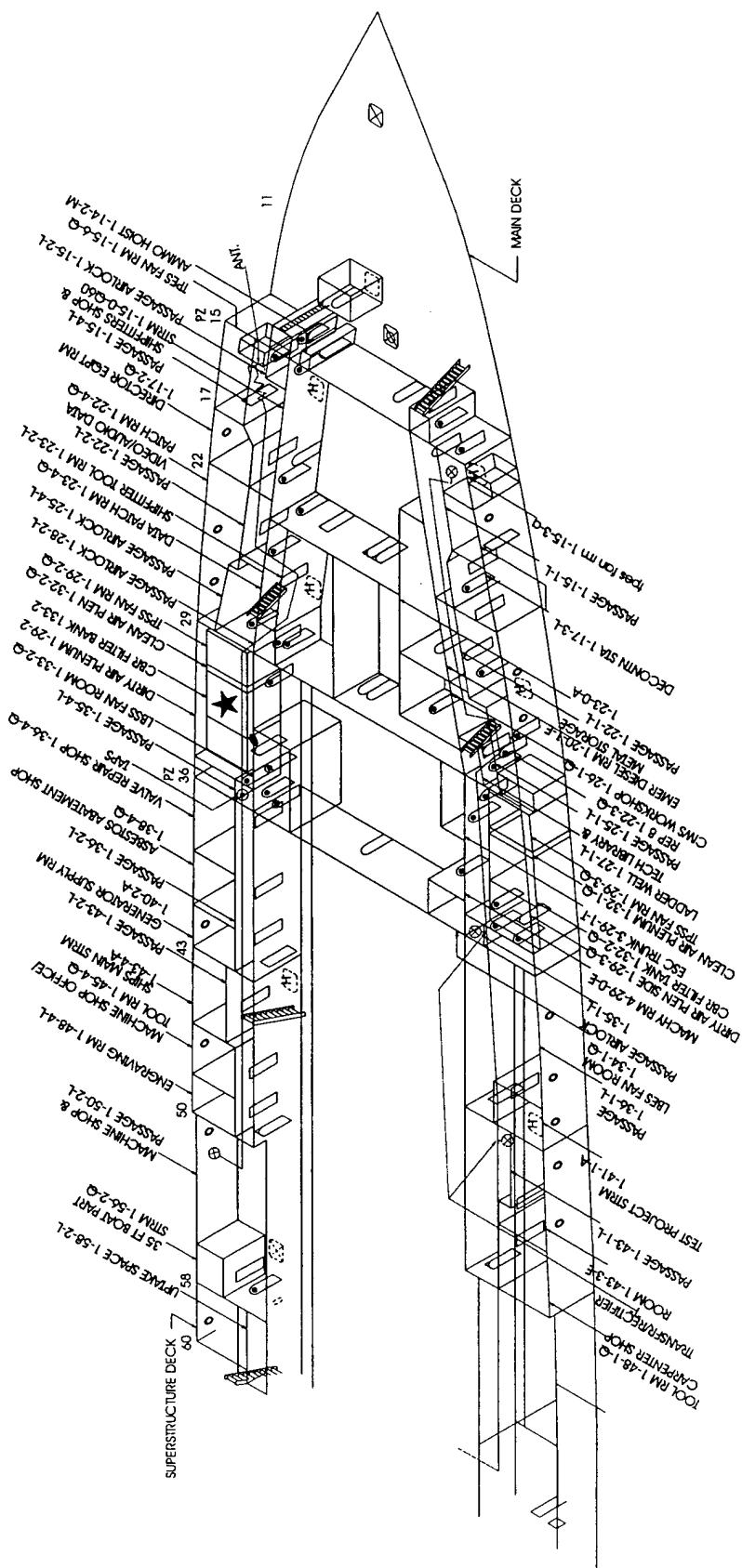


Fig. 5 — Portion of DC plates showing Main Deck

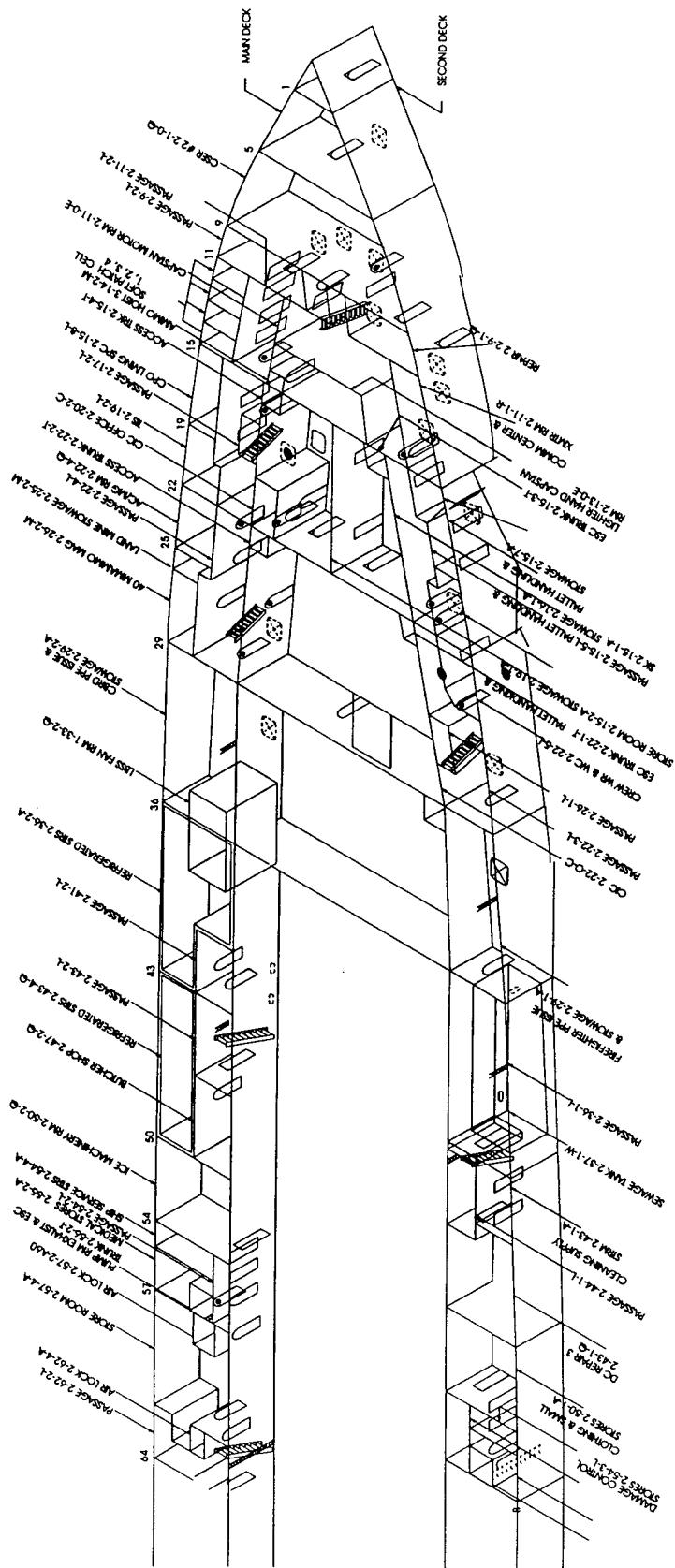


Fig. 6 — Portion of DC plates showing Second Deck

SHIPBOARD FAMILIARIZATION (PHASE I)

MISSION STATEMENT

GOAL: To navigate through the forward section of the *ex-Shadwell* under *reduced visibility conditions* and locate a hole on the starboard side of the ship.

NAVIGATION MISSION: The navigation mission will be initiated on the Superstructure Deck at WTD 01-29-1, which is located forward of the Mess Deck. You will proceed to the starboard side and traverse down an inclined ladder to the Main Deck. You will then locate and traverse down a second inclined ladder to the Second Deck and proceed forward to compartment 2-22-3-L (ARMY OFFR'S & NON COMMWR/WC) and note the hole in the side of the ship.

TEST PROTOCOL: The following general guidelines will be applicable to all test participants during the Phase I testing:

- (1) Each test participant will traverse through the test area individually.
- (2) Each participant will don and activate an OBA prior to initiating the navigation mission.
(NOTE: A smoke simulator will be fitted to the facepiece.)
- (3) Each participant should strive to transit the test area in an expeditious manner.
- (4) Misdirections will be verbally corrected, "Wrong way."
- (5) Test participants will be required to maintain *existing* door closures.
- (6) The mission will be complete when the test participant touches the hole in the side of the ship.

Fig. 7 — Mission statement for Phase I

For the VE rehearsal, participants practiced their mission immersed in an accurate model of the test space. The VE rehearsal was performed in three steps. Step 1 was the "magic carpet ride" where the motion through the space was controlled by the computer, and the participant was instructed to look around and become familiar themselves with the area. This step was narrated to point out notable features in the model. During Step 2, the participant navigated through the space by operating the motion and interaction controls exactly as they had done during the VE practice session. For Step 3, the participant again controlled the motion and interaction, but simulated smoke, which limited visibility to about 0.9 m (3 ft), was added to the environment. Timing measurements were collected during the VE rehearsal, both the time it took for the participants to walk through in clear visibility and in reduced visibility. The VE rehearsal was also recorded on video. A 1-min rest period was required when the participant removed the HMD, and a check for simulator sickness symptoms was taken between each of the VE rehearsal steps.

Before beginning the Phase I test run, the participants donned the faceplate from an Oxygen Breathing Apparatus (OBA) that had attached to it a smoke simulator faceplate, the Smokepaq-1 from Vision Technologies. The device was adjusted so that visibility was reduced to approximately 0.9 m (3 ft). A *Shadwell* safety team member accompanied the participant throughout the test and collected data on the number of wrong turns taken and the number of times assistance was provided with doors.

3.2 Ship Familiarization Results

The initial analysis strongly supports the effectiveness of VE rehearsal. The VE training group navigated more quickly in Phase I than the traditional group. The VE group was on average 30 s faster over a 2-min run. The VE group averaged 1 min, 54 s while the tradition group averaged 2 min, 38 s. In Phase I, all of the traditional training group participants made wrong turns whereas only one member of the VE group made a wrong turn.

As an indicator of how fast the Phase I test could be traversed under ideal training conditions, five experienced firefighters from Afloat Training Group Middle Pacific (ATG MIDPAC) completed the Phase I navigation run after rehearsing in the actual shipboard test space. The firefighters studied DC plates for 10 min and were given three practice runs similar to those given to the VE group. First, they were guided through the route; second they walked the route under clear visibility; and third, they walked the route wearing reduced visibility goggles set to approximately 0.9 m (3 ft), like the smoke simulator faceplate. After training, the firefighters ran the route wearing an OBA with a smoke simulator faceplate. The fastest time was 1 min, 4 s. This indicates that VE training is almost as good as training in the actual space, but it is significantly better than training with just ship's diagrams.

4.0 FIREFIGHTING IN VIRTUAL ENVIRONMENT

4.1 Approach

The fire tests were conducted in the forward area of the ex-USS *Shadwell*, on the First (Main) and Second Decks between FR 9 and FR 22 (Figs. 5 and 6). The actual test area was on the Second Deck between FR 15 and FR 22 (Fig. 6). This area had been modified from its original configuration for the 1994 Attack Team Workshop [5] by the addition of the fore-to-aft centerline bulkhead. The compartment to port of the centerline bulkhead is designated as the Storage Area (2-15-2-A), and the compartment to starboard is designated as the General Store Keeping (GSK) Office (2-15-1-Q). The centerline bulkhead has two joiner doors, one forward at FR 16 and another aft at FR 20, to provide access between these two compartments.

The fire area was in the aft portion of the storage area compartment (Fig. 6). Access to the fire area was via the starboard passageway through water-tight door QAWTD 2-17-1 into GSK, and then though the forward joiner door into the fire space. Repair 2 (2-9-1-Q) was used as the staging area for the attack team. The fo'c'sle area forward of the Ship Fitter's Shop (1-15-0-E) on the Main Deck, and Combat Information Center (CIC) aft (2-22-0-C) on the Second Deck served as emergency escape and muster areas.

The Phase II tests involved combating a Class A steady-state fire using a horizontal attack through an uninvolved adjacent compartment. All tests were identical, with the fire threat consisting of a single wood crib that was partially obstructed by metal lockers. This forced the attack team to advance well into the fire compartment before being able to initiate a direct attack on the seat of the fire. To further increase the difficulty of the firefighting evolution, none of the test participants (team leaders) was permitted to observe the layout of the fire compartment prior to taking the test. The hose team for each test was assembled from a pool of firefighters that had previous experience combating fires in the Class A fire area and, therefore, were familiar with the layout of the space but were to function totally under the control of the team leader.

The scope of these tests was limited to the control and extinguishment of a steady-state Class A fire confined to a single compartment. Fire spread was not considered; e.g., boundaries were not set, and there was no active desmoking/ventilation. The variables that could be controlled, such as supply and exhaust ventilation and preburn time, were held constant for all tests. The only variable that was changed from test to test was the type of familiarization training provided to the test participant (team leader), e.g., VE system or DC plates. Additionally, no test participant was involved in more than one test in the capacity of team leader.

4.2 Test Participants

All test participants and hose team members were Fleet personnel. The test participants were the same as those used in the familiarization tests described in Section 2.0. Test participants included eight men from the USS *Inchon* and four women from the USS *Puget Sound*. The hose team consisted of personnel from ATG MIDPAC. All test participants were qualified in accordance with the Personnel Qualification Standard (PQS) for DC to at least the Basic Firefighting 304 (Hoseman) level. Some of the participants were additionally qualified to the Advanced Firefighting 308 (Nozzlemaster/Team Leader) level. The major difference between the two groups was that the traditional group had only standard DC plates with which to train and familiarize while the VE group used both DC plates and the VE system.

4.3 Fire Threat

Based on data obtained during the 1994 Attack Team Workshop [5], a repeatable, moderate-to-severe fire threat was developed. This fire threat was intended to represent a steady-state fire involving Class A combustible materials (i.e., paper and wood). The single fire source was capable of creating near flashover conditions in the fire compartment with flames impinging on the overhead and upper layer temperatures in the range 400°-600° C (752°-1112° F). To provide further realism and challenges to the attack team, obstructions—including metal lockers and partitions—were placed between the fire source and its access within the fire compartment. This forced the attack team to advance well into the space to directly attack and extinguish the source of the fire. The ease with which this task was completed was dependent, at least in part, on the team leader's understanding of the compartment layout.

4.4 Experimental Setup

The layouts of the First (Main) and Second Deck test areas are shown in Figs. 5 and 6. Dimensional details of these areas are presented in Appendix A of Ref. 5. The staging area for the attack team was in the athwartship passageway adjacent to Repair 2 (2-9-1-Q). The team leader dressed out on the fo'c'sle prior to joining the rest of the attack team at Repair 2. Accesses used by the attack team to reach the fire compartment included QAWTD 2-15-1, QAWTD 2-17-1, and JD 2-17-0. The dimensions of the quick-acting watertight doors were 170 × 66 cm (66 × 26 in.), and the joiner doors in the centerline bulkhead were 210 × 61 cm (84 × 24 in.). Emergency exit routes available to the attack team were FD 2-22-1 to the CIC aft safety area or QAWTD 2-17-1 and QAWTD 2-15-1 back to Repair 2 and then up to the fo'c'sle via the booby hatch at FR 11.

Simulation of a typical storage area fire having a single fire source was provided by burning a wood crib. To further simulate a storage area fire and to make the attack more challenging, metal panels and lockers were located around the compartment such that they obstructed direct access to the fire source. The exact locations of the fire source and obstructions are shown in Fig. 8. The wood crib was made from red oak sticks cut to a nominal size of 5 × 5 × 120 cm (2 × 2 × 48 in.) and was assembled in place on a metal grate support stand that was 58-cm (23-in.) high (Fig. 9). The square wood crib had a total of 10 layers of sticks. Each layer had 10 sticks, with successive layers being placed perpendicular to each other. A 91-cm (36-in.) square metal pan located under the support stand was used to hold the initiating fuel. The initiating fuel was 19 L (5 gal) of commercial grade n-heptane. The metal panels used as obstructions were all 1.2-m (4-ft) high (Fig. 10).

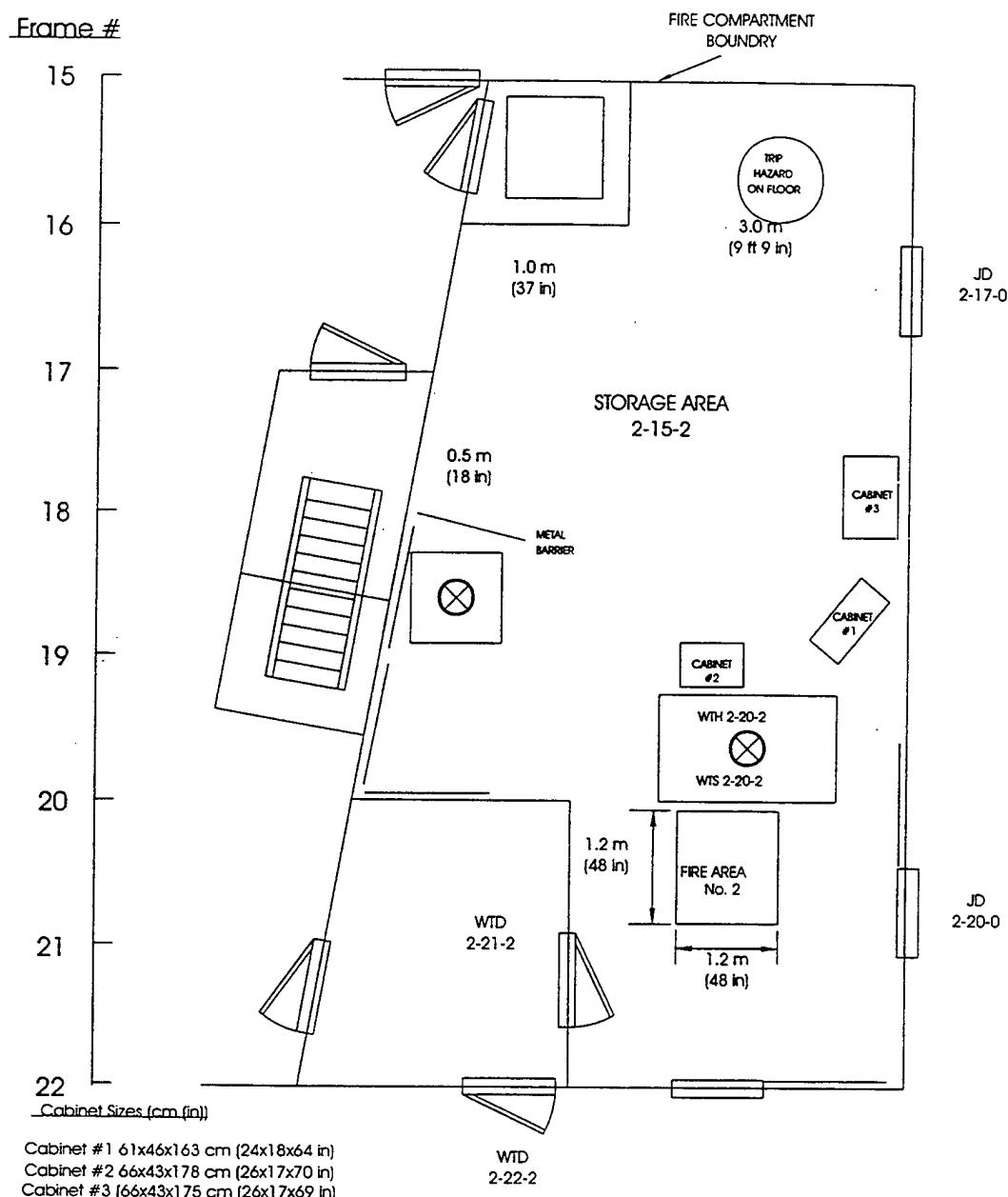


Fig. 8 — Second deck fire source and obstruction layout plan view, FR 15-22

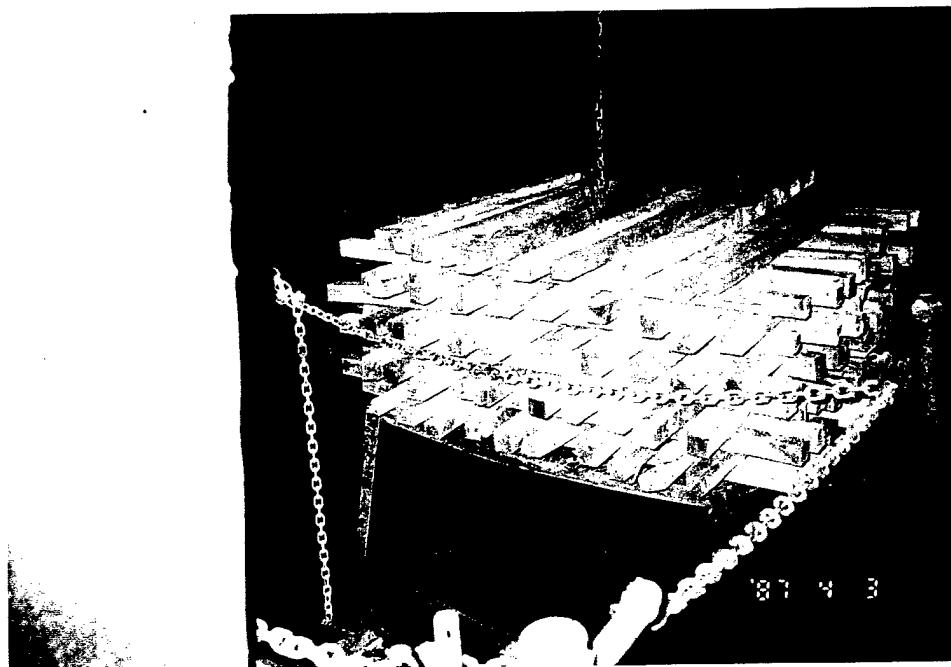


Fig. 9 — Wood crib assembled on support stand with initiating fuel plan below (shown without obstructions)

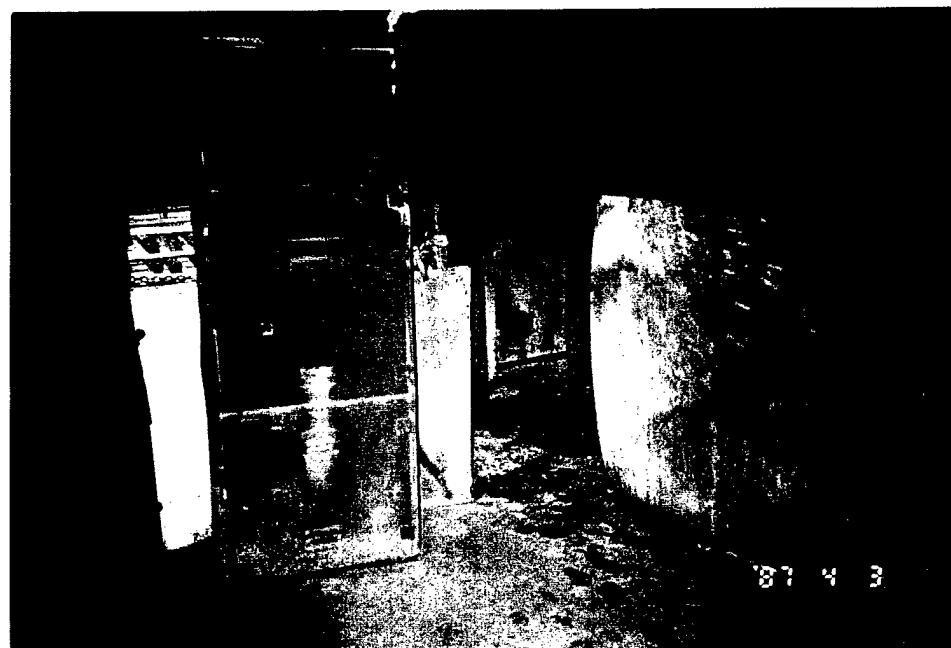


Fig. 10 — Obstructions located in front of and adjacent to fire source

Ventilation for these tests was supplied from the ship's ventilation systems—TPSS (Total Protection Supply System) and TPES (Total Protection Exhaust System). This ventilation nomenclature is derived from a collective protection system prototype that is being installed on the DDG-51 class ships [6]. The supply system outlet for the test area was located near the aft bulkhead of the storage area in the overhead and had a measured flow of 3,822 Lpm (135 cfm). The exhaust inlet was located at approximately the center of the storage area in the overhead and had a measured flow of 44,369 Lpm (1,567 cfm). Additional fresh air was supplied to the fire compartment during the fire build-up phase from CIC aft (2-22-0-C) via the CIC office (2-20-2-Q). This was accomplished by leaving WTD 2-22-2 fully open and throttling the air flow with WTD 2-21-2. Prior to the attack team entering the fire space, WTD 2-21-2 was closed. The f-stops on the exhaust system shafts located at FR 15 (both port and starboard) were left open to provide a natural ventilation path for the test area. Both of these exhaust paths discharged to weather at the 02 level. The fans on these systems were not activated during the firefighting evolution; however, after the fire was declared out, the fan on the starboard system (E1-15-1) was turned on to expedite desmoking of the test area.

All attack team members were provided with standard Navy protective equipment for these tests. This included the one-piece Navy firefighters ensemble (NSN 8415-01-300-6558) with DC/firefighters helmet (NSN 84515-01-271-8069), antiflash hood (NSN 8415-001-268-3473), antiflash gloves (NSN 8415-01-267-9661), firefighter's gloves (NSN 8415-01-296-5766), fireman's rubber boots (NSN 8405-00-753-5940), and Type A-4 OBA (NSN 4240-00-616-2857). Chemlights (chemically activated markers), Model 95270-53 manufactured by American Cyanamid were attached to the OBA harness (one each on the front and back) to make test participant (team leader) easier to identify in the smoke-filled environment of the test area.

The attack handline was a 15-m (50-ft) length of 3.8-cm (1.5-in.) fabric-jacketed hose (NSN 4210-00-255-6234) equipped with a Type 1, 3.8-cm (1.5-in.) 360 Lpm (95 gpm) varinozzle (IAW MIL-N-24408). This handline was attached to the fire plug in the starboard passageway at FR 19 (FP 2-19-1). A 1.9-cm (0.75-in.) hoseline was also used by safety team members for overhaul and mop-up operations.

The locations of all instrumentation installed for these tests are shown in Figs. 11 and 12. The symbol legend for the instruments shown in these figures is provided in Table 1 along with notes on instrumentation that was out of service for specific tests. Key instruments located in the Second Deck test area are shown on Fig. 12 and are described below.

4.4.1 Thermocouples

Type K inconel-sheathed thermocouples, 3.2-mm (0.13-in.) outside diameter and 1.6-mm (0.06-in.) outside diameter were used to measure air, overhead, and crib flame temperatures. Two vertical thermocouple strings mounted on stands located at FR 18 on the port side of the fire compartment (2-15-2) and at FR 19 on the starboard side of the fire compartment (2-15-2) measured air temperatures. The thermocouples were mounted on the stands at 46 cm, 91 cm, 140 cm, 180 cm, 230 cm, and 274 cm (18 in., 36 in., 54 in., 72 in., 90 in., and 108 in.) above the deck. Overhead thermocouples mounted 15 cm (6 in.) below the overhead were located in the bays formed by the overhead structural framing immediately aft of FR 16, FR 18, and FR 20 in the storage area.

Thermocouples mounted in a similar manner were located in the bays immediately aft of FR 16 and FR 17 in the GSK compartment. These thermocouples measured the overhead temperatures. The forward two bays in the storage area had three thermocouples each, positioned 71 cm, 220 cm, and 361 cm (28 in., 85 in., and 172 in.) out from the center-line bulkhead. The aftmost bay in the storage area, and both bays in the GSK area had only two thermocouples each, positioned 71 cm and 220 cm (28 in. and 85 in.) out from the center-line bulkhead. Three thermocouples were extended down from the overhead at the fire source location to measure crib flame temperatures. These thermocouples were centrally located at the bottom, middle, and 31 cm (12 in.) above the top of the crib.

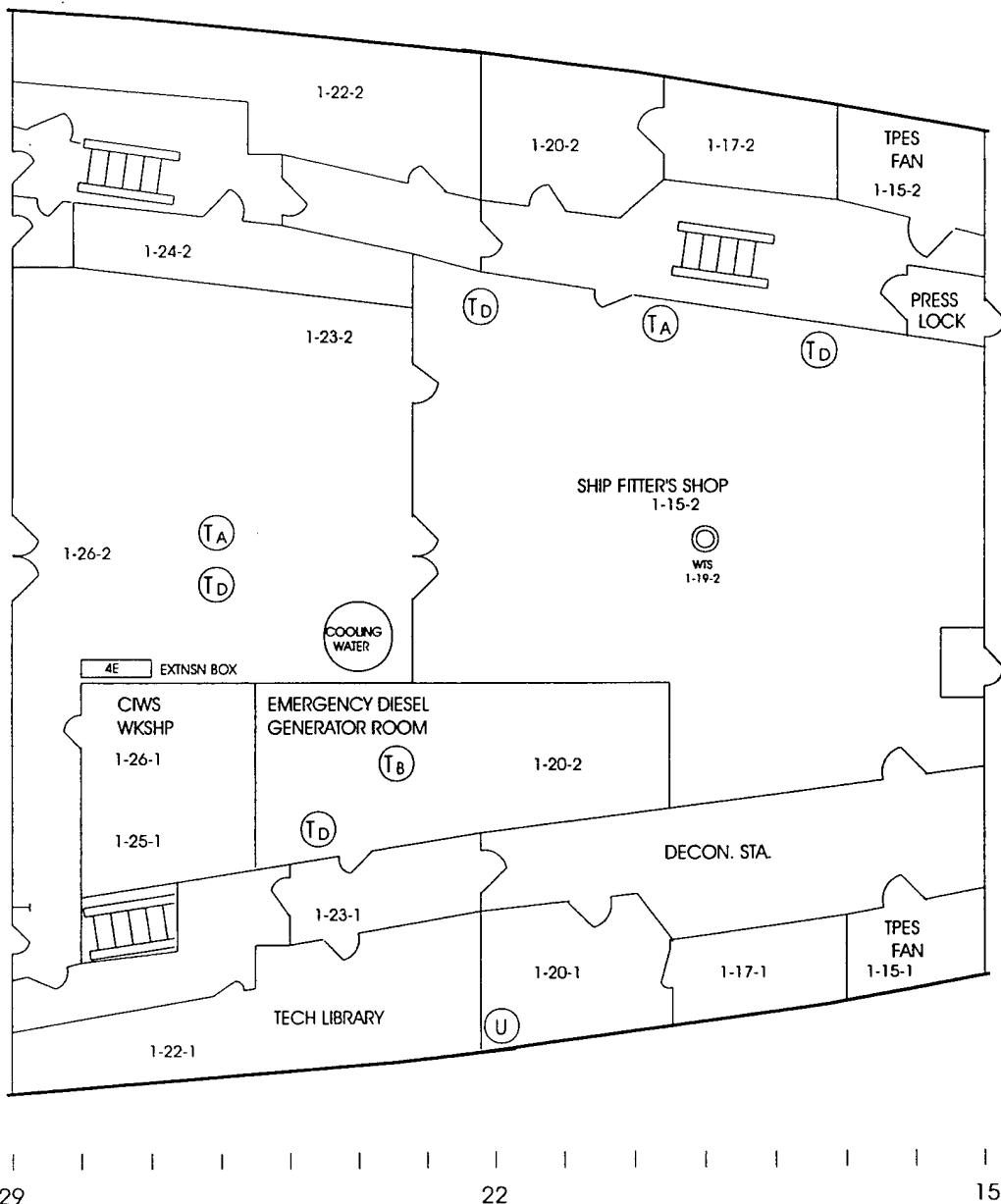


Fig. 11 – First (Main) Deck instrumentation layout plan view, FR 15-29

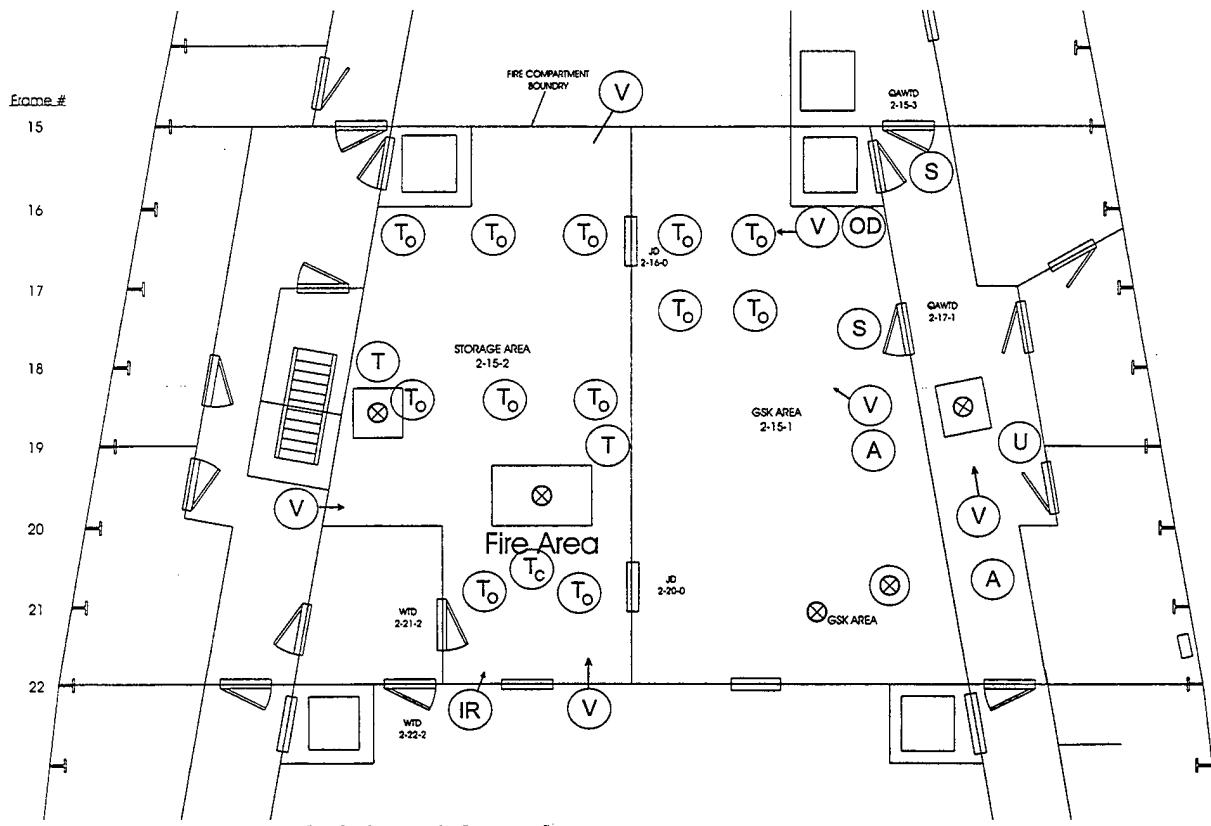


Fig. 12. Second Deck test area instrumentation layout plan view, ER 15-23

Table 1. Instrumentation Key

Symbol	Description
A	Audio
V	Camera, arrow indicates direction of view
IR	Camera (infrared), arrow indicates direction of view
*C	Calorimeter, at 1.5 m (5 ft) above the deck
S	Door microswitch
T	Thermocouple tree, thermocouples starting at 46 cm (18-in.) above the deck and spaced 46 cm (18-in.) apart
T _O	Overhead thermocouple, 15 cm (6-in.) below overhead
U	Ultrasonic water flowmeter
OD	Optical density meter (LED type), 1.5 m (5 ft) above the deck
*T _A	Air thermocouples, one each at 46 cm (18 in.) and 150 cm (60 in.) above the deck
T _C	Crib thermocouple, total of three, positioned at bottom, middle, and 31 cm (12-in.) above top of crib
*T _D	Deck surface thermocouples

*Not shown in Fig. 12.

4.4.2 Heat Flux Transducers

Total heat flux was measured in the fire compartment (storage area) by a calorimeter mounted on the center-line bulkhead just aft of FR 15 at 1.5 m (5 ft) above the deck. The mounting bracket for this instrument was oriented so that it was aimed directly at the wood crib location. Two different units were used to obtain these measurements. Both of the calorimeters (Medtherm Corp. serial numbers 85029 for tests VE01-VE06 and 75131 for tests VE07-VE12) had a range of 0-57 kW/m² (0-5.0 Btu/ft²s). For tests VE07-VE12, total heat flux was also measured in the GSK area by a calorimeter mounted 1.5 m (5 ft) above the deck on the aft-facing bulkhead of the exhaust shaft supplying exhaust fan E1-15-1. The mounting bracket for this instrument was oriented so that it viewed the forward joiner door JD 2-17-0. Calorimeter 85029, described above, was used to collect these data.

4.4.3 Optical Density Meters

Smoke obscuration was measured at two locations using optical density meters (ODM). The first was mounted in the GSK area on the aft bulkhead of the exhaust shaft supplying exhaust fan E1-15-1. The second was located in the starboard passageway at FR 20. The ODMs were installed so that the beam projected vertically, with the center of the beam path located 1.5 m (5 ft) above the deck. These units measured the percentage of light transmitted and had a range of 0-100%.

4.4.4 Ultrasonic Flowmeters

An ultrasonic flowmeter (Controltron 9000 series) was used to monitor water flow from fire plug FP 2-19-3. This flowmeter was installed on the vertical riser supplying the fire-plug hose connection.

4.5 Test Procedures

Prior to each test, the test participant was given a Team Leader Review, which addressed safety issues, firefighting tactics and strategies, and duties of the participant team leader. The test participant then proceeded to a mission review, which provided the locations of necessary firefighting equipment and the location of the fire. After the mission review was completed, the test participant was given 10 min for mission rehearsal with DC plates and the mission statement. Test participants in the traditional group then proceeded directly to the exercise brief. Participants in the VE group were given approximately 15 min for VE rehearsal before proceeding to the exercise brief, which was given by the team leader with members of the hose team present. The mission statement was reviewed and the hose team was instructed on tactics, nozzle settings, and hand signals. Once this brief was completed, all members of the attack team went to the fo'c'sle to get dressed out for the tests, after which the hose team members proceeded down to Repair 2 while the test participant remained on the fo'c'sle.

When all hose team members were in place outside of Repair 2, the fire area was cleared of all personnel except designated safety team members. The designated safety officer during these tests patrolled the forward section of the ship, primarily on the Second Deck. Two safety team members were positioned aft of WTD 2-22-2 to pour and ignite the fuel and to keep watch on the fire while it burned. An additional safety team member was positioned in the starboard passageway to monitor the attack team and assist in emergency evacuations. A final safety team member was stationed on the fo'c'sle to monitor normal movements of the attack team into and out of the Second Deck test area. At least one safety team member equipped with a portable Navy Firefighting Thermal Imager (NFTI) was located in the fire compartment at all times when test participants were extinguishing the fire.

Prior to pouring fuel, the pretest check list was completed. The fire pump was brought on line at 827 kPa (120 psi). This resulted in a nominal flow rate at the varinozzle of approximately 360 Lpm (95 gpm). The proper ventilation configuration for the fire threat was aligned including fan settings and accesses to the spaces. Video recorders were started and data acquisition was initiated. Once the data acquisition system had begun collecting data, the test director gave the command to have fuel poured into the pan located beneath the crib. When fueling was completed, the fire was ignited. The fire was allowed to preburn for approximately 7 or 8 min. During the preburn period, fresh air to the fire space was throttled via WTD 2-21-2 to regulate the fuel burning rate. After the preburn period was complete and it was confirmed by the temperature data that the fire was well involved, the test participant was allowed to proceed to the Second Deck test area where the participants joined the rest of the attack team. It took between 10 and 15 min for the attack team to get fully dressed out (including OBAs) and staged at Repair 2. Once all attack team members were ready, WTD 2-21-2 was shut tight. The attack team then proceeded from Repair 2, manned and charged the hoseline at FP 2-19-3, and proceeded through GSK into the fire compartment. Some of the attack teams did not charge the hose line until they were in position in GSK at JD 2-17-0. Firefighting continued until either the test participant (team leader) or a safety team member declared the fire out. The attack team then backed out of the space and returned to the fo'c'sle. The test participant was debriefed immediately after removing the firefighting gear. The control room maintained continuous radio contact with the safety team members, recording events from their radio communications as well as from the video supplied by the cameras located around the test area. A total of 12 tests were conducted. They are numbered VE01 through VE12 in the order in which they were conducted.

4.6 Results

The overhead thermocouples and the upper three thermocouples on each string in the storage area provide a measure of test repeatability. Crib temperatures also provide a measure of crib involvement.

Table 2 presents upper-layer gas temperature and maximum wood crib temperature data (i.e., maximum of all three thermocouples) at three different time steps. Upper-layer gas-temperature data include the average of all fire compartment overhead thermocouples and the average of all string-mounted thermocouples located 180 cm (72 in.) or more above the deck. The time steps used for this evaluation include the time interval from 7 to 12 min, the time the attack team left Repair 2, and the time the attack team entered the fire compartment. The time interval of 7 to 12 min was chosen because this represents the true growth period of the fire, after the initiating fuel was consumed.

Based on the data presented in Table 2, the repeatability for all tests except test VE11 was very good. Mean values for all tests are given, along with the standard deviations. With the exception of the maximum wood crib temperature for the period 7 to 12 min, the standard deviations are all in the range of 2% to 5% of their respective mean values, indicating good repeatability of the fire threat. The standard deviation for the maximum wood crib temperature for the period 7 to 12 min is 7.5%, but this value is directly affected by how long it takes for the initiating fuel to burn. If it took longer than 7 min to burn the initiating fuel, then the maximum flame temperature for the 7-to-12 min period would be expected to be higher. This, in fact, may have been the case in some of the tests.

The data for test VE11 show that temperatures were generally about 100°-200° C (180°-360° F) lower than for the other tests. For this test, 80% of the wood used to construct the crib was previously burned wet wood. Reduced temperatures should be expected in this situation because a greater portion of the energy produced by the combustion process is being used to convert the moisture in the wood into a vapor. Also, because the wood was previously burned, the surface area available for combustion was reduced, which, in turn, results in a lower heat release rate.

Table 2 — Upper Layer Gas and Wood Crib Temperatures at Various Times

Test Number	Temperature (°C (°F))								
	Maximum for Period 7-12 Minutes			Attack Team Leaves Repair 2			Attack Team Enters Fire Compartment		
	Average Overhead	Maximum Wood Crib	Avg. Upper TC Strings	Average Overhead	Maximum Wood Crib	Avg. Upper TC Strings	Average Overhead	Maximum Wood Crib	Avg. Upper TC Strings
VE01	564 (1047)	982 (1800)	464 (867)	541 (1006)	739 (1362)	443 (829)	509 (948)	694 (1281)	427 (801)
VE02	541 (1006)	953 (1747)	448 (838)	539 (1002)	750 (1382)	445 (833)	534 (993)	751 (1394)	444 (831)
VE03	547 (1017)	988 (1810)	470 (878)	538 (1000)	766 (1411)	445 (833)	525 (977)	748 (1378)	433 (811)
VE04	538 (1000)	1081 (1978)	452 (846)	532 (990)	752 (1386)	438 (820)	529 (984)	753 (1387)	433 (811)
VE05	502 (936)	936 (1717)	406 (763)	500 (932)	706 (1303)	403 (757)	502 (936)	718 (1324)	409 (769)
VE06	539 (1002)	1114 (2037)	441 (826)	520 (968)	712 (1314)	431 (808)	526 (979)	711 (1312)	436 (817)
VE07	520 (968)	883 (1621)	425 (797)	515 (959)	727 (1341)	422 (792)	512 (954)	710 (1310)	423 (793)
VE08	523 (973)	1015 (1859)	442 (828)	521 (970)	741 (1366)	433 (811)	513 (955)	716 (1321)	430 (806)
VE09	513 (955)	961 (1762)	434 (813)	511 (952)	712 (1314)	432 (810)	511 (952)	704 (1299)	435 (815)
VE10	502 (936)	969 (1776)	410 (770)	491 (916)	671 (1240)	401 (784)	492 (918)	685 (1265)	404 (759)
VE11	398 (748)	1076 (1969)	317 (603)	395 (743)	613 (1135)	313 (595)	404 (759)	623 (1153)	523 (613)
VE12	511 (952)	873 (1603)	432 (810)	509 (948)	714 (1317)	413 (775)	505 (941)	711 (1312)	411 (772)
Mean	527 (981)	978 (1792)	439 (822)	520 (968)	726 (1339)	428 (802)	514 (957)	718 (1324)	426 (799)
Standard Deviation	20 (36)	73 (131)	20 (36)	17 (31)	27 (49)	16 (29)	13 (23)	23 (41)	13 (23)

Note: Calculations for mean and standard deviation values do not include data for Test VE11.

In order to compare the test results, measures of performance that evaluate the heat, steam, and fire threat experienced by the attack team as well as water usage and cooling/extinguishing efficiency were developed. Similar measures of performance were used to evaluate data from the 1994 Fog Attack Workshop tests [5]. Note that these measures of performance are dependent primarily on the attack team's knowledge of proper firefighting tactics and procedures. Because the VE system did not address firefighting tactics or procedures, these measures of performance provide an evaluation that is independent of the training method. The measures of performance used for this evaluation include the following:

- (a) wood crib temperatures;
- (b) average fire compartment overhead temperature;
- (c) average of upper three-string thermocouples vs average of lower three-string thermocouples for each string; and
- (d) cumulative total water used.

The wood crib temperatures provide an indication of how quickly the fire was knocked down, whether it flared up, and when it was finally extinguished. The average overhead temperatures provide an indication of the thermal threat that existed at the overhead and how well it was controlled. The overhead temperature data also provide an indication of when reflashes occurred, which, in turn, are an indication of extinguishing effectiveness. The thermocouple string data demonstrate how much the thermal balance within the fire compartment was disturbed. The cumulative total water-usage data are a measure of extinguishing efficiency.

Graphical presentation of this data is provided in the Appendix. These graphs are based on time zero being when the attack team departed from Repair 2 and passed through QAWTD 2-15-1. Up to that point in time, the test participants were unaffected by the fire conditions. Once the attack team entered into the starboard passageway, they were exposed to the smoke and heat being generated by the fire. In reviewing these graphs, note that the cumulative total water flow data include the flow necessary to charge the hose line. This volume accounts for 35 L (9.2 gal) of the total flow.

An analysis of firefighting response times was also performed by plotting the time to complete specific tasks on time lines. These time lines tracked the following events:

- (a) test participant arrives at Repair 2;
- (b) attack team departs from Repair 2;
- (c) hose line manned and charged;
- (d) attack team enters GSK;
- (e) attack team enters fire compartment;
- (f) initial attack (water discharge) at the seat of the fire;
- (g) fire declared out; and
- (h) attack team departs from the fire compartment.

Items (a) through (f) allow a comparison of the traditional vs VE training methods because completion of these tasks is a function of familiarity with the space. Items (g) and (h) are dependent more on knowledge of firefighting tactics and procedures and, therefore, are not expected to be good indicators of the type of training received. As with the graphs, time zero for this evaluation began when the attack team departed from Repair 2. A graphical representation of these data is provided in Fig. 13.

4.7 Discussion

Firefighter-response-time data presented in Fig. 13 indicate how well the attack team, under the direction of the test participant (team leader) was able to navigate the test space under realistic fire conditions. Selecting meaningful timing measures was difficult because different attack teams performed the required tasks in different sequences. For example, some teams charged the hose line in the starboard passageway rather than the GSK. In this case, it is not practical to evaluate the elapsed time required to man the hose line and enter GSK. In addition, data on times for the fire to be declared out and the attack team departed the fire compartment were not recorded for all tests and could not be evaluated.

Table 3 summarizes key values taken from the quantitative data presented in the Appendix. Subjects VE01, VE03, VE05, VE07, VE09, and VE11 were in the traditional training group that only used the ship's DC plates to develop their attack. VE02, VE04, VE06, VE08, VE10, and VE12 were in the VE training group that, in addition to studying DC plates, rehearsed their firefighting strategy in VE. The data suggest that VE rehearsal improves performance.

A comparison of the variance of the two groups for the key data measures suggests that while the subjects' skills at extinguishing the fire were similar, the VE training group was better organized and more consistent in their performance. Formal hypothesis testing fails to show significant difference between groups; we did not expect it to because of the limited number of Navy firefighters available for the demonstration (there were only six in each group). With such a small number of subjects, the statistical power is low, and statistical significance is difficult to reach. The variance is a useful measure in this case because it summarizes how differently a subject performs from all other subjects as well as from the mean. The larger the variance, the more subjects within that group perform differently from one another.

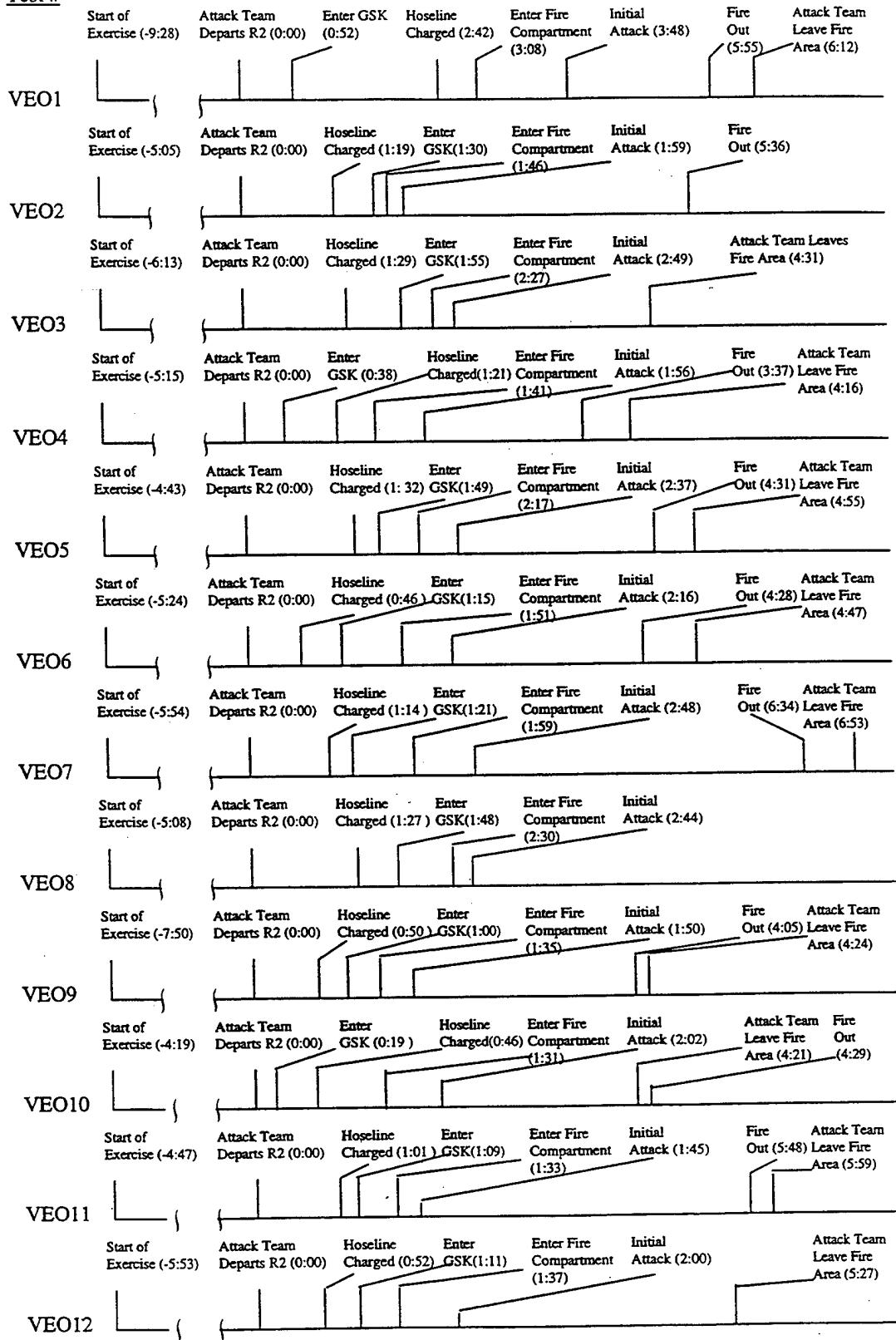
Test #

Fig. 13 — Event timelines for tests VEO1-VEO12

Table 3 — Summary of Key Measure of Performance Values

Test Number	Time After Leaving Repair 2 to Initiate Fire Attack (s)	Time After Initial Attack to Reduce All Wood Crib Temperatures to <150°C (302°F) (s)	Total Reduction in Average Overhead Temperature at 2 Min After Initial Attack (°C (°F))	Total Quantity of Water Used (L (gal)) (Corrected for Volume Needed to Fill Hoseline)
VE01	228	39	166 (299)	10 (2.7)
VE02	119	99	222 (399)	87 (23)
VE03	169	211	200 (360)	220 (59)
VE04	116	64	223 (401)	8.3 (2.2)
VE05	157	70	200 (360)	66 (18)
VE06	136	77	201 (362)	110 (28)
VE07	168	99	209 (376)	180 (47)
VE08	164	71	197 (355)	70 (19)
VE09	110	246	188 (339)	37 (10)
VE10	122	118	205 (368)	48 (13)
VE11	105	164	177 (319)	97 (26)
VE12	120	96	196 (353)	240 (62)

Figure 14 shows a pair of box plots, one for each group, for each of the four key measures in Table 3. We have presented box plots (also called a box and whisker plots) because a box plot gives a picture of the variance (or spread) of the distribution for the data. The horizontal line in the interior of the box is located at the median of the data. The height of the box is equal to the interquartile distance (IQD), which is the difference between the third quartile of the data and the first quartile. The height of the box shows the variance if there are no outliers; two boxes of the same height indicate equal variance. If there are outliers, the size of the box is still a reasonable approximation of the variance. The whiskers (the dotted lines extending from the top and bottom of the box) extend to the extreme values of the data. Unusually deviant data (defined as data that are 1.5 times the IQD) are shown as lines above or below. The variances are markedly different for the top two data sets and similar for the bottom two in Fig. 14.

For the data for elapse time from departing Repair 2 to beginning the initial attack (Fig. 14(a)), the variance for the traditional group is more than six times greater than the VE group's. This difference suggests that the VE training group was more consistent in their approach during this phase. A formal test of the difference of variances is significant at $p < 0.06$, which is suggestive given the outlier in the VE group data. The VE group averages 26.7 s faster performance. More striking is the difference in performance between groups in the time to achieve extinguishment of the wood crib (i.e., the time required to reduce all wood crib temperatures below 150°C (302°F) (Fig. 14(b)). The variance is 16 times greater for the traditional group than the VE group. A formal hypothesis test of the difference of variances is highly significant at $p < 0.009$. (Note that the time for traditional group subject VE03 was thrown out because the fire was allowed to reflash to evaluate a thermal imager.) The traditional group is, on average, 36.1 s lower. The data suggest that rehearsing in VE helped the group perform the firefighting task in a more focused and consistent way.

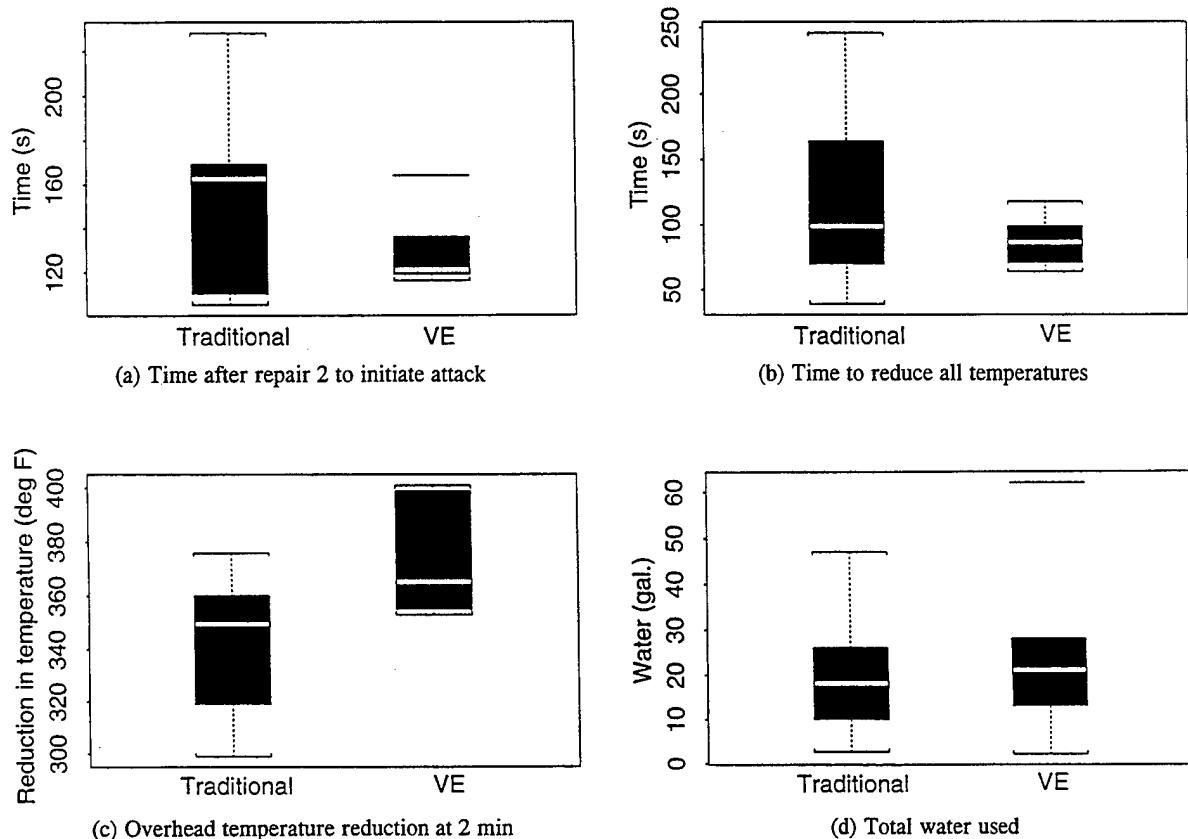


Fig. 14 — Box plots of key measures

The performance of both groups is similar for the bottom two measures in Fig. 14, which rely more on firefighter training. VE did help slightly to produce more consistent behavior, which can be seen in a variance that is somewhat less for the VE group in both cases. The variance for the traditional group for total reduction in average overhead temperature at 2 min after the initial attack is less than twice that of the VE group's (Fig. 14(c)). The VE group averages 26.2 s slower. These data are fairly reliable even with the reflashes. (Again, data for subject VE03 of the tradition training group were thrown out.) The graphical data for average overhead temperature show that the reflashes that did occur (as indicated by the wood crib temperature data) were not large enough to be measured at the overhead and did not pose a serious thermal threat. A formal test of difference in variances is not significant. The cumulative total water flow data are also similar (Fig. 14(d)). The difference in variance is only 124.7 (with the traditional group's larger) and is not significant. The average difference in amount is only 3.79 gal more for the VE group.

5.0 CONCLUSIONS

Based on the quantitative data presented, the following conclusions can be drawn:

- The repeatability of the fire threat was good for all tests except test VE11. Standard deviations for the data evaluated were typically in the range of 2% to 5% of the mean values.
- The analysis of the difference in variance for the time after leaving Repair 2 and the time after initial attack to reduce wood crib temperatures suggests that rehearsal in VE helps firefighters become more focused and consistent in their performance.

(c) The part of the task that depends less on organizational strategy and more on firefighter training benefited less from VE rehearsal. Total reduction of average overhead temperature at 2 min after the initial attack and the total quantity of water used show a more consistent performance.

6.0 REFERENCES

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Appendix A
MEASURES-OF-PERFORMANCE GRAPHS

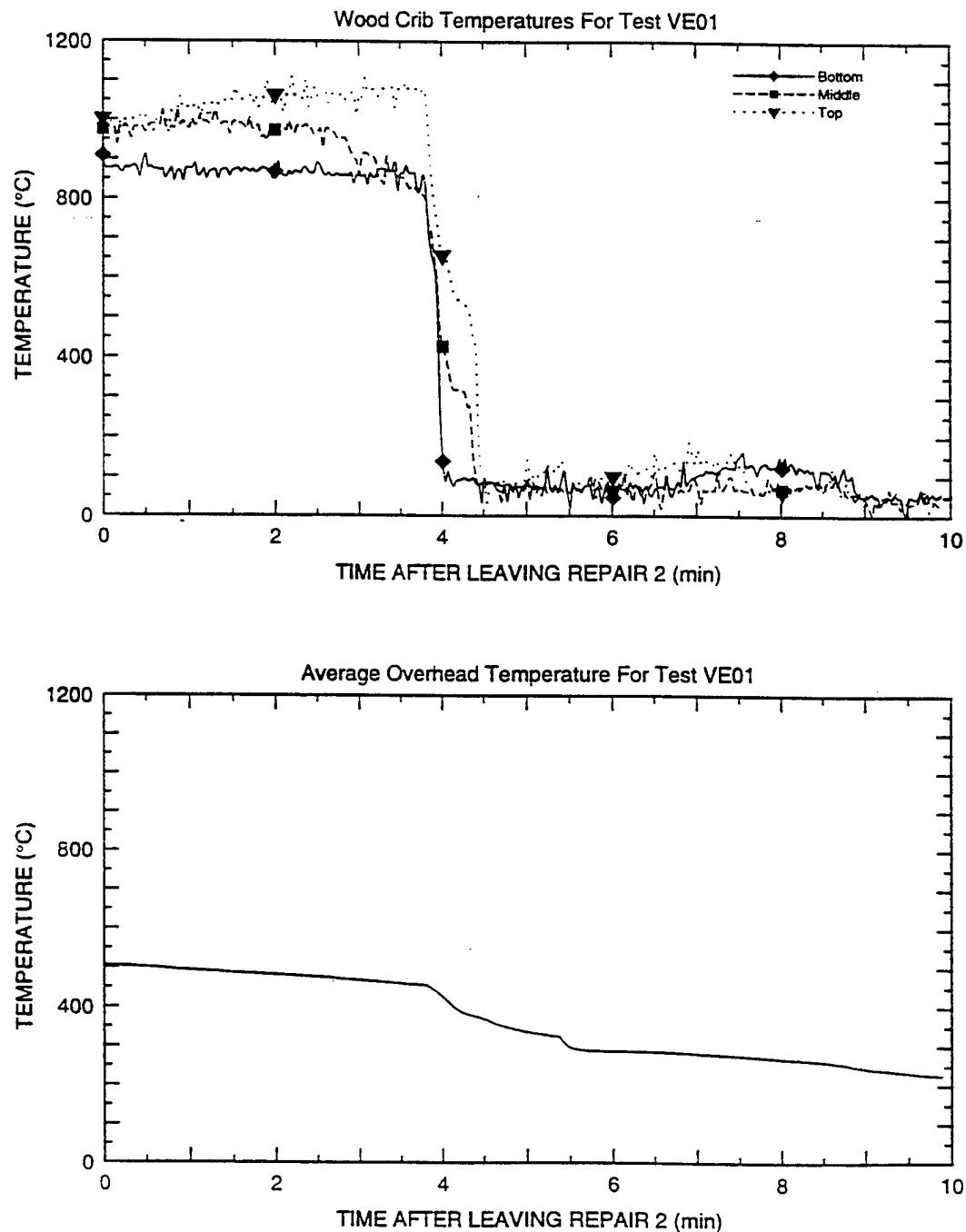


Fig. A1 — Wood crib and average overhead temperatures for test VE01

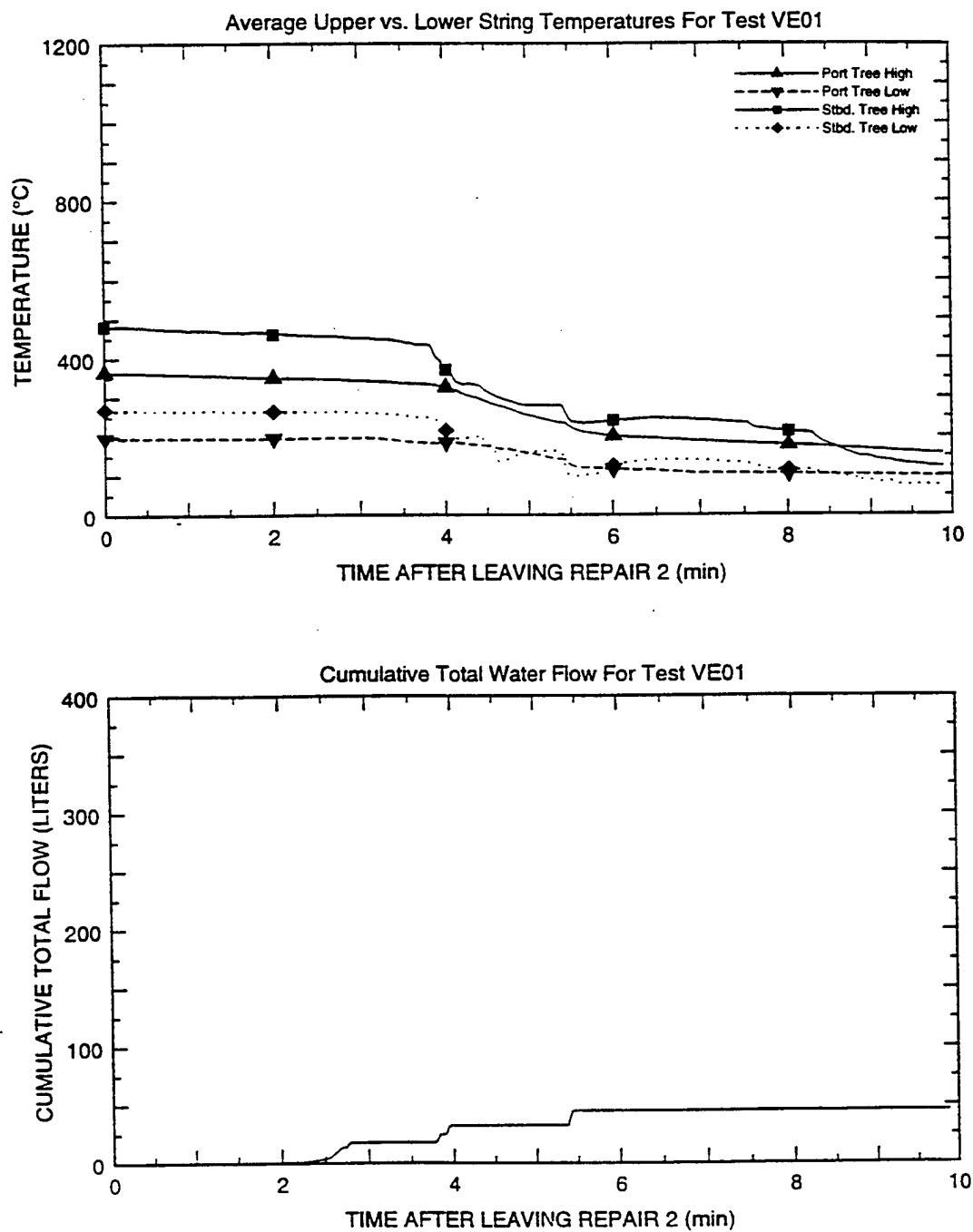


Fig. A2 —Average string temperatures and cumulative total water flow for test VE01

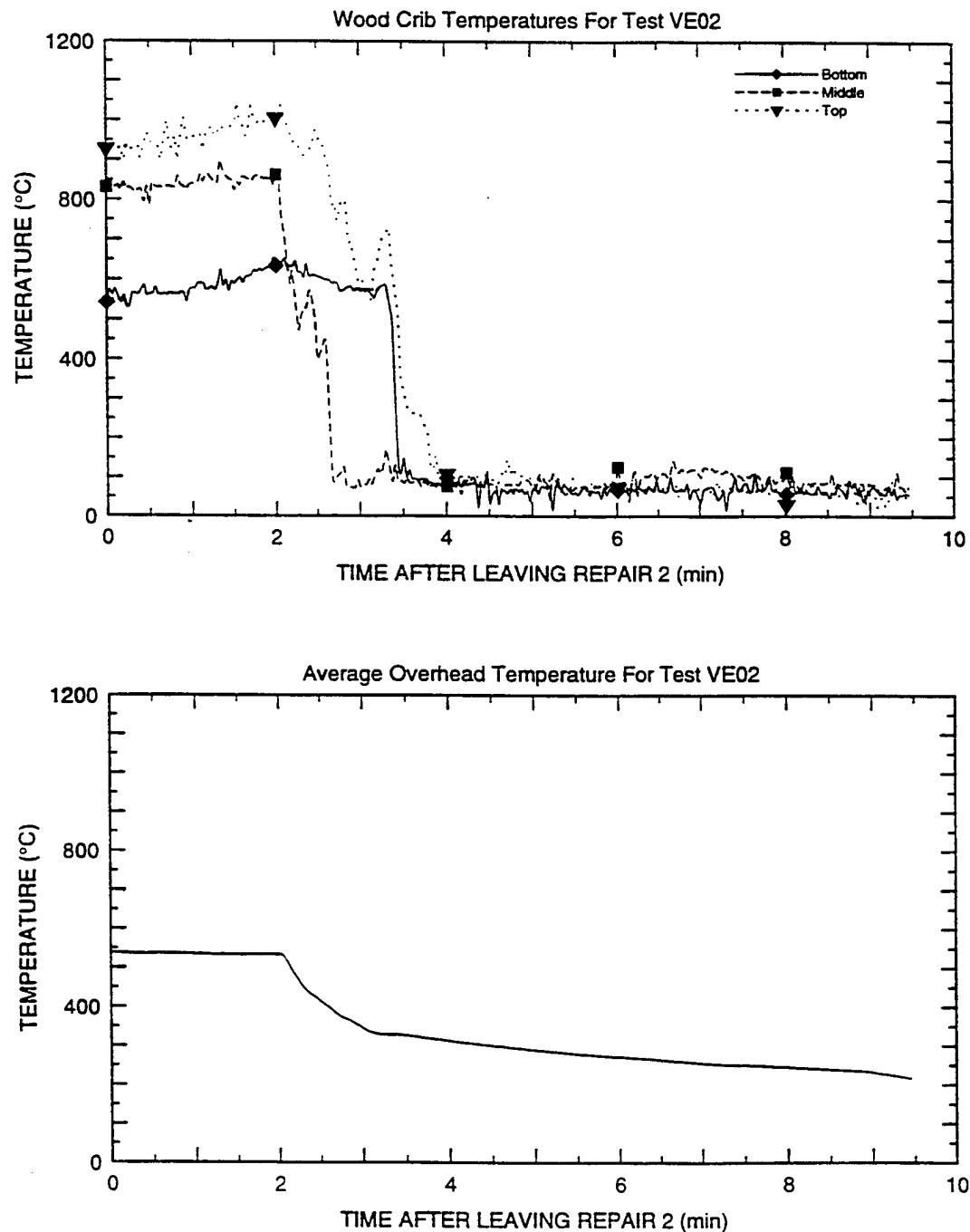


Fig. A3 — Wood crib and average overhead temperatures for test VE02

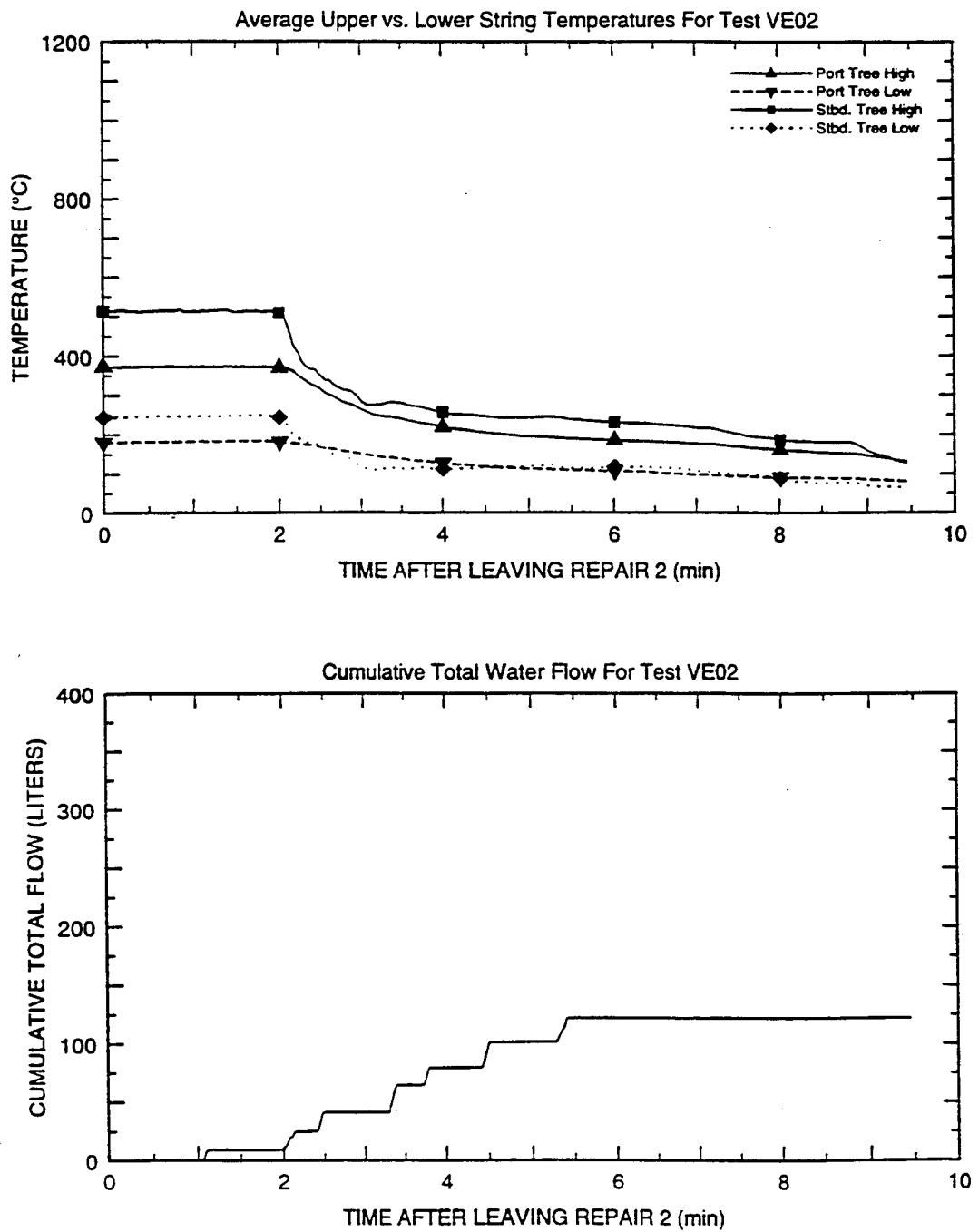


Fig. A4 — Average string temperatures and cumulative total water flow for test VE02

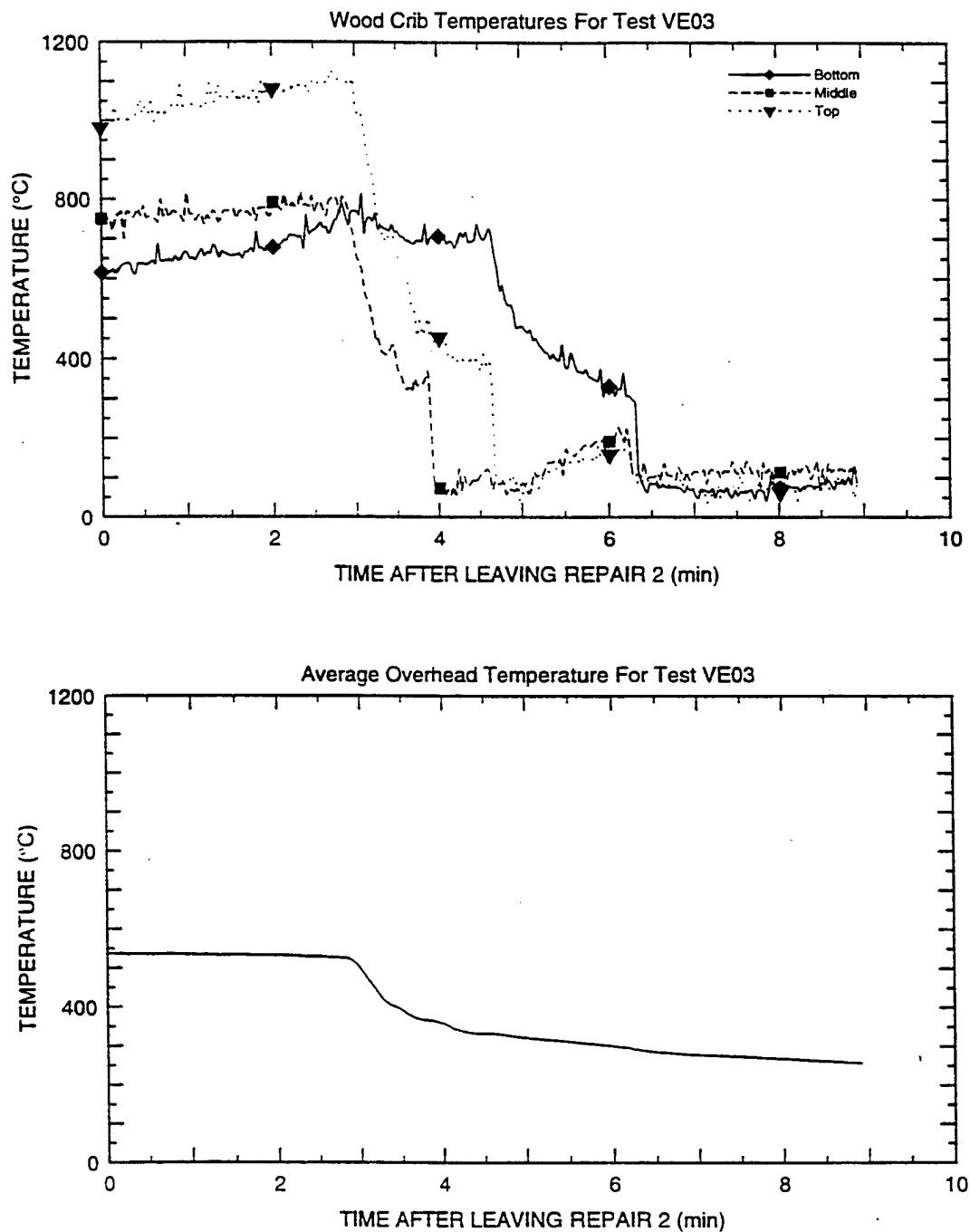


Fig. A5 — Wood crib and average overhead temperatures for test VE03

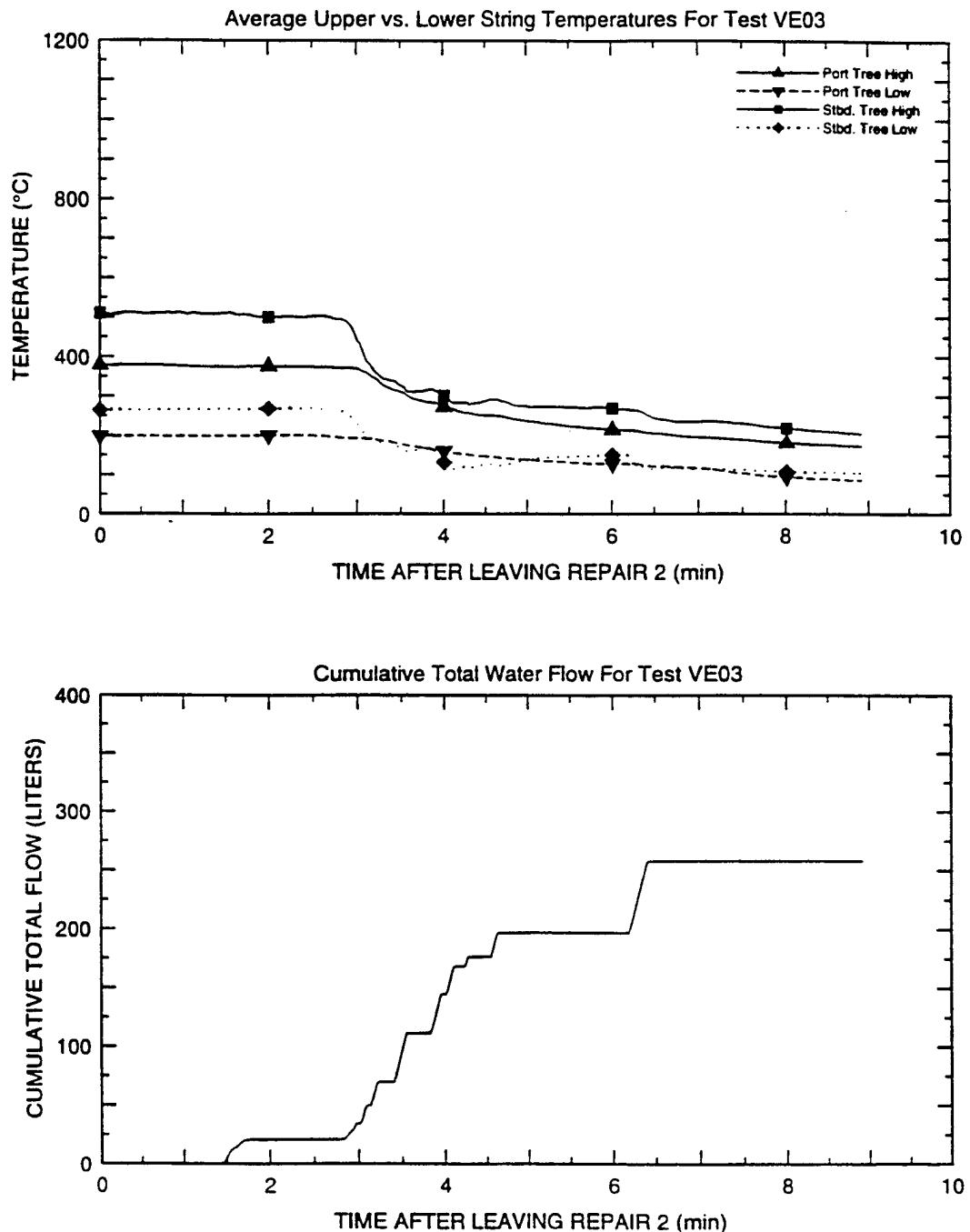


Fig. A6 —Average string temperatures and cumulative total water flow for test VE03

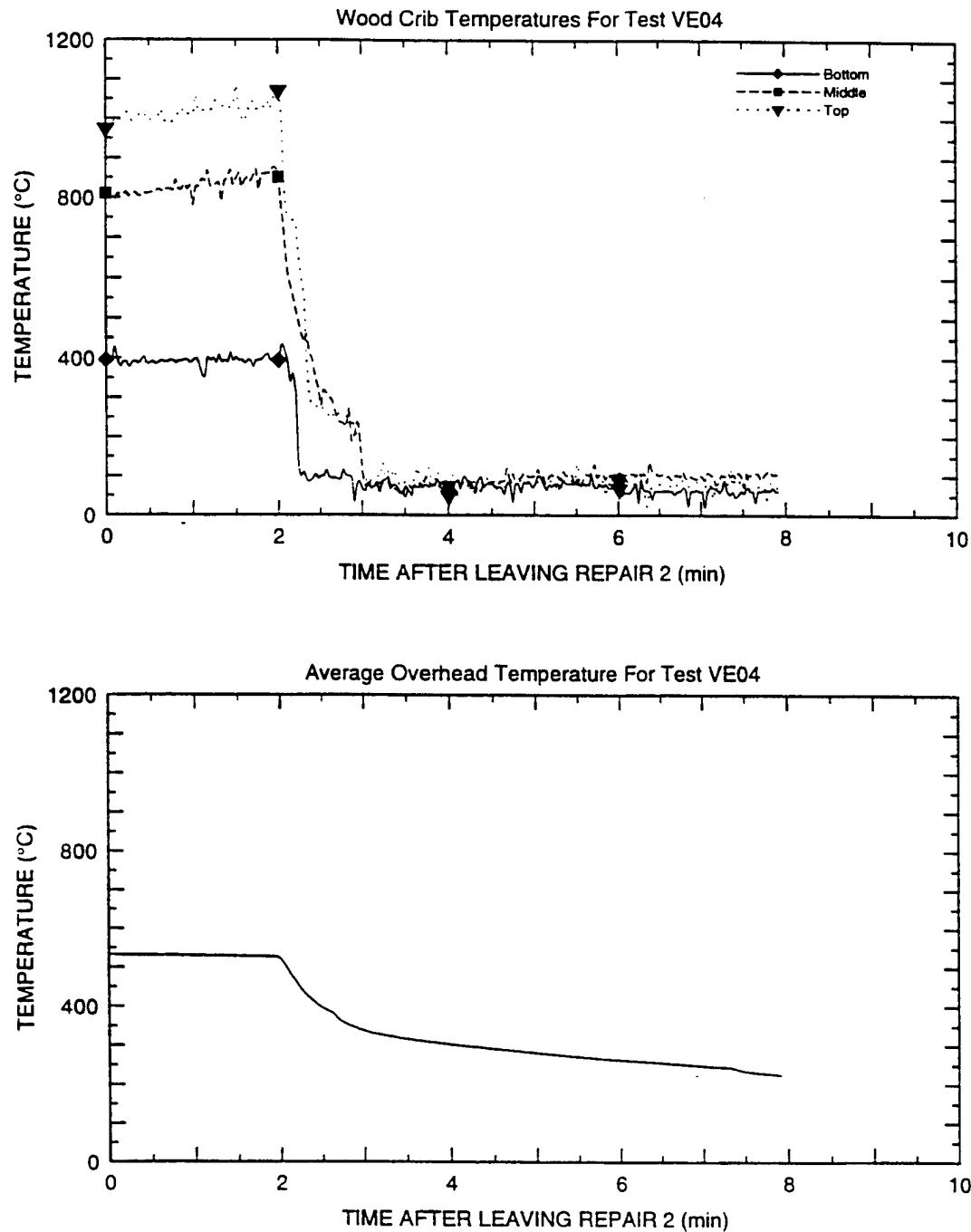


Fig. A7 — Wood crib and average overhead temperatures for test VE04

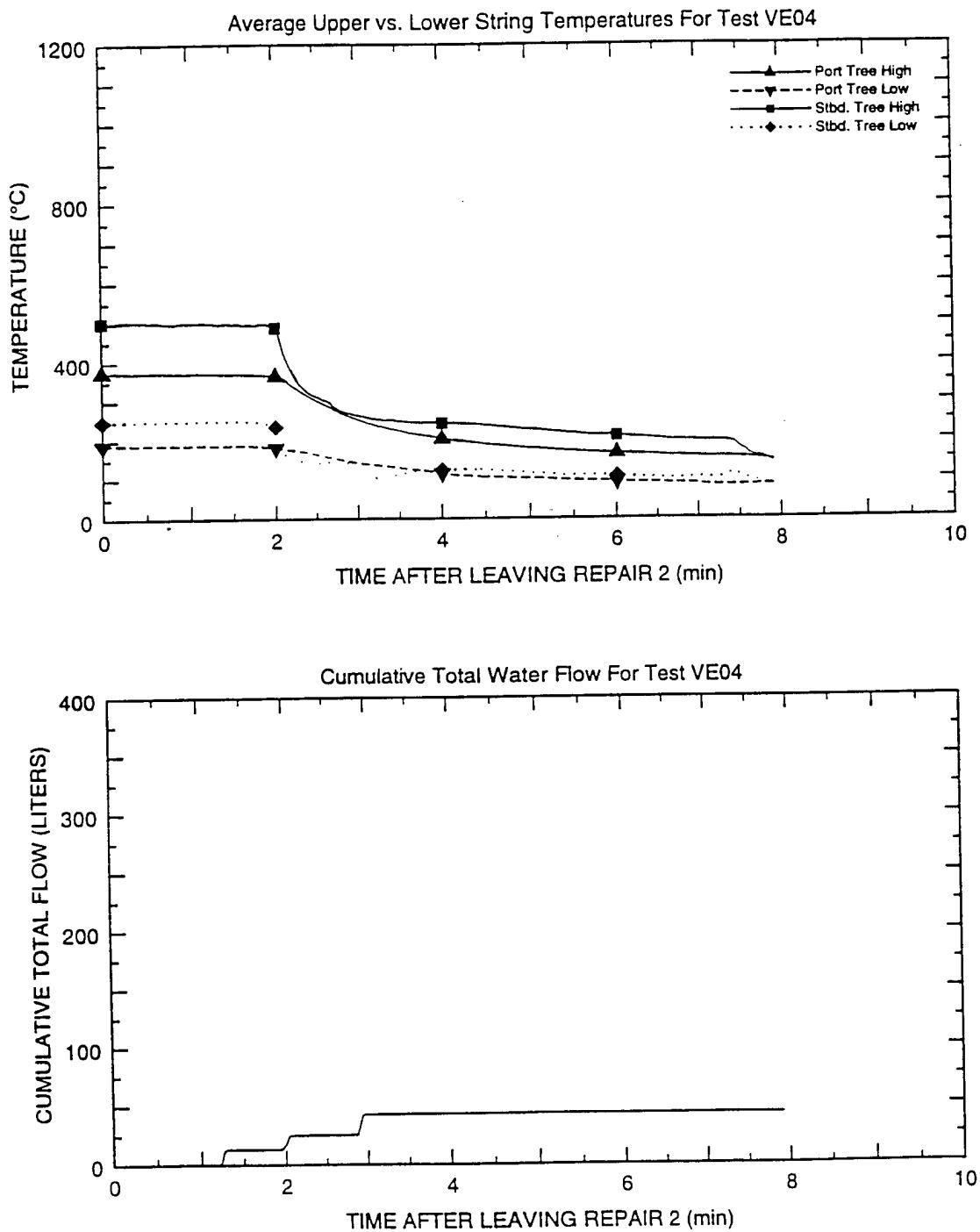


Fig. A8 — Average string temperatures and cumulative total water flow for test VE04

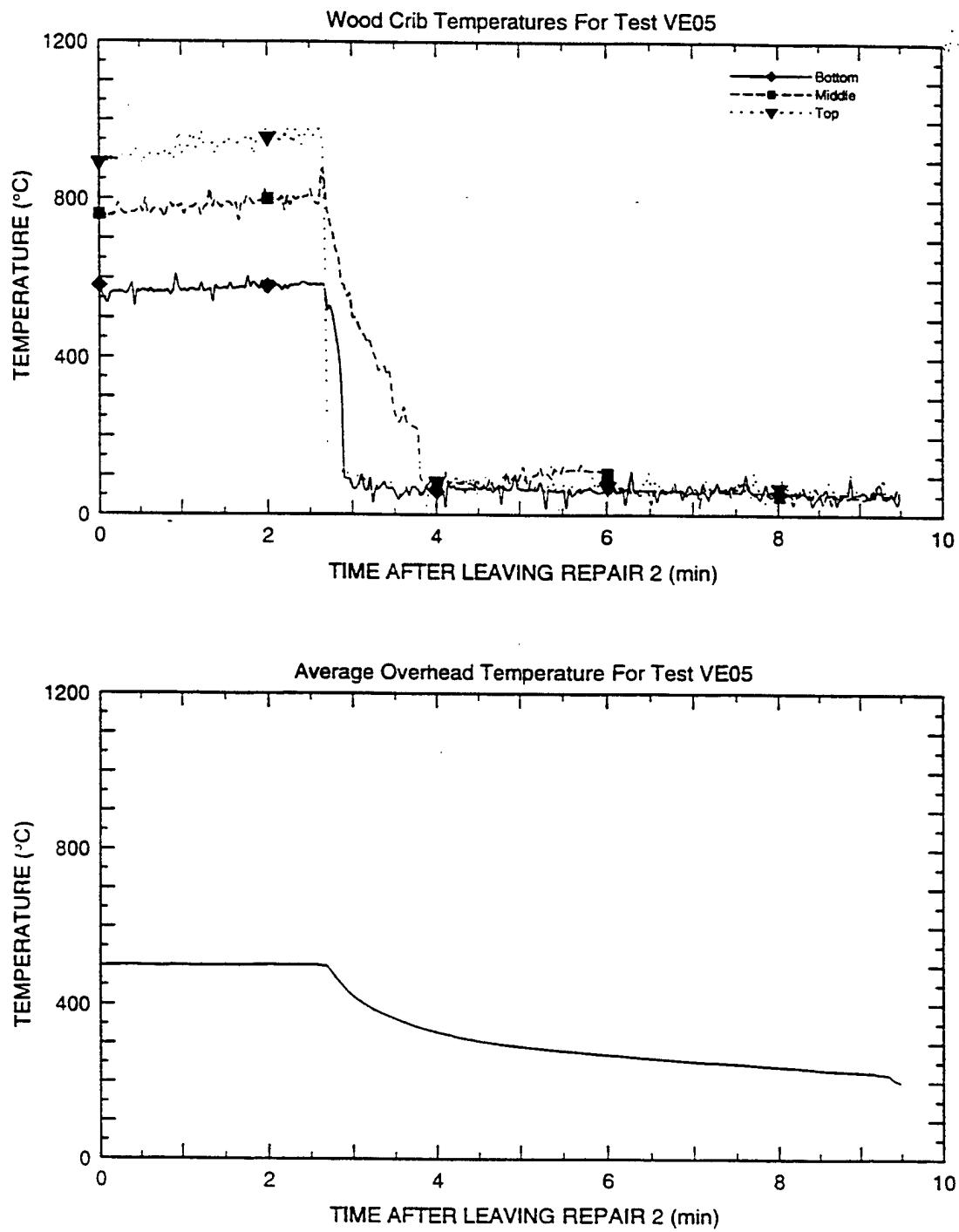


Fig. A9 — Wood crib and average overhead temperatures for test VE05

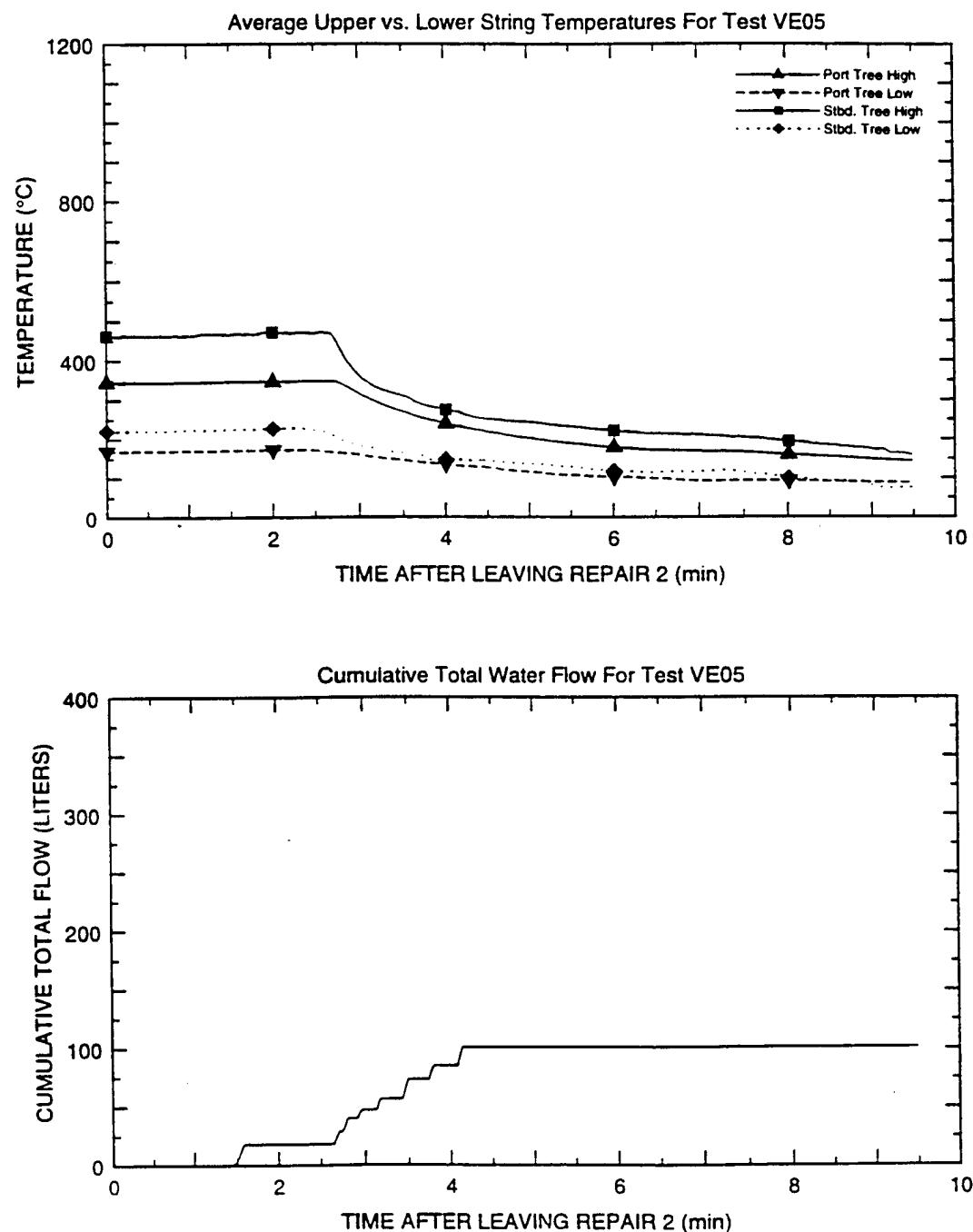


Fig. A10 — Average string temperatures and cumulative total water flow for test VE05

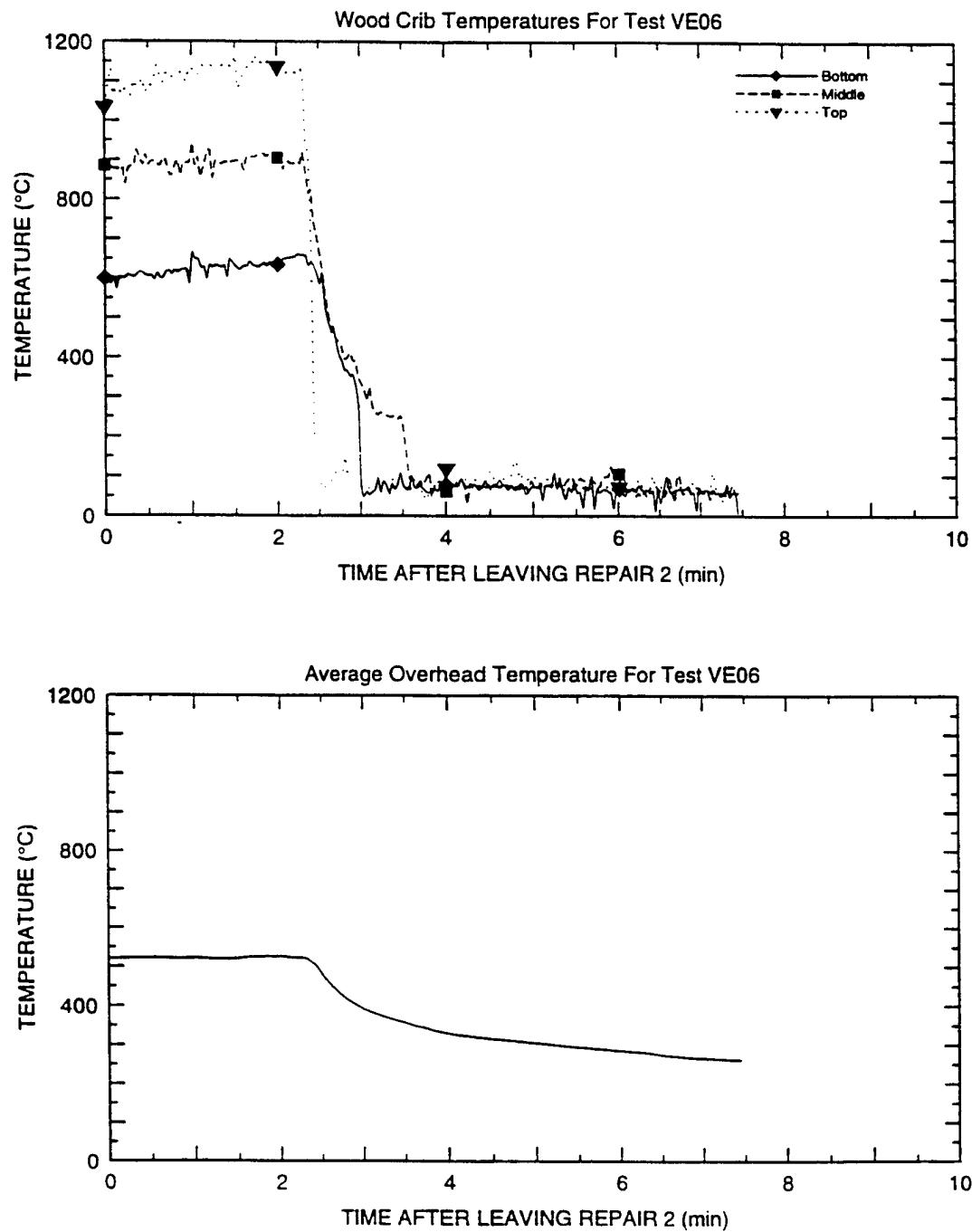


Fig. A11 — Wood crib and average overhead temperatures for test VE06

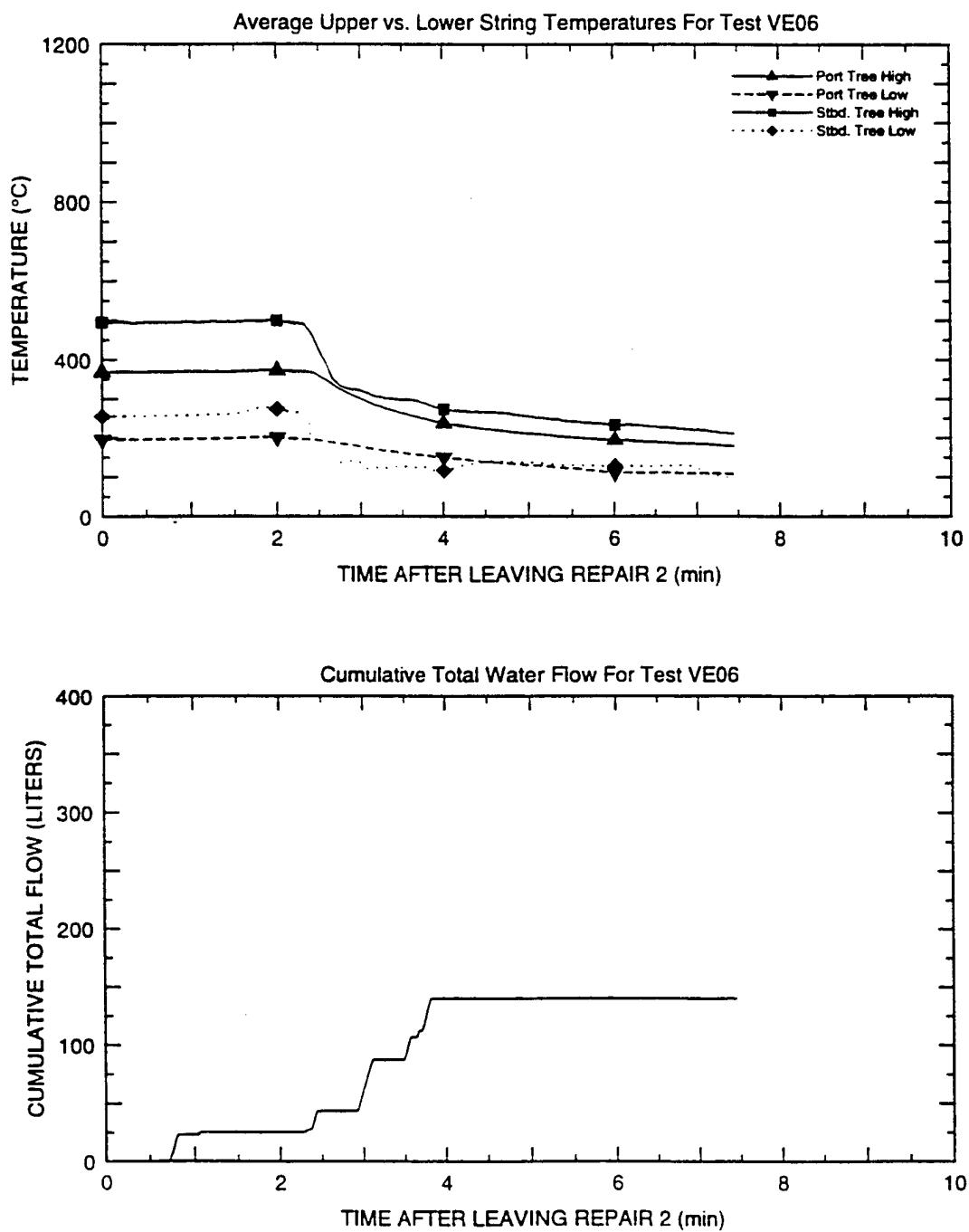


Fig. A12 — Average string temperatures and cumulative total water flow for test VE06

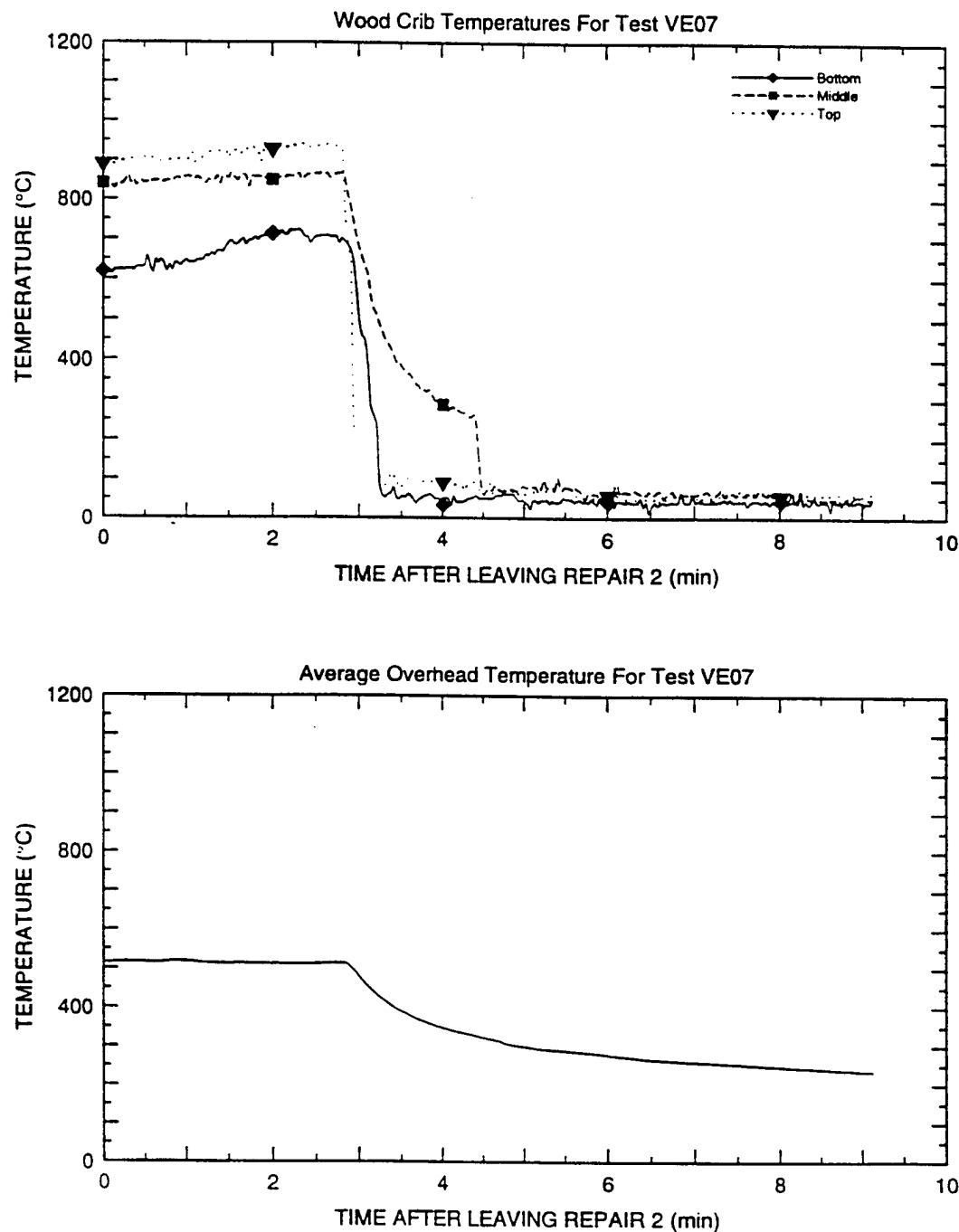


Fig. A13 — Wood crib and average overhead temperatures for test VE07

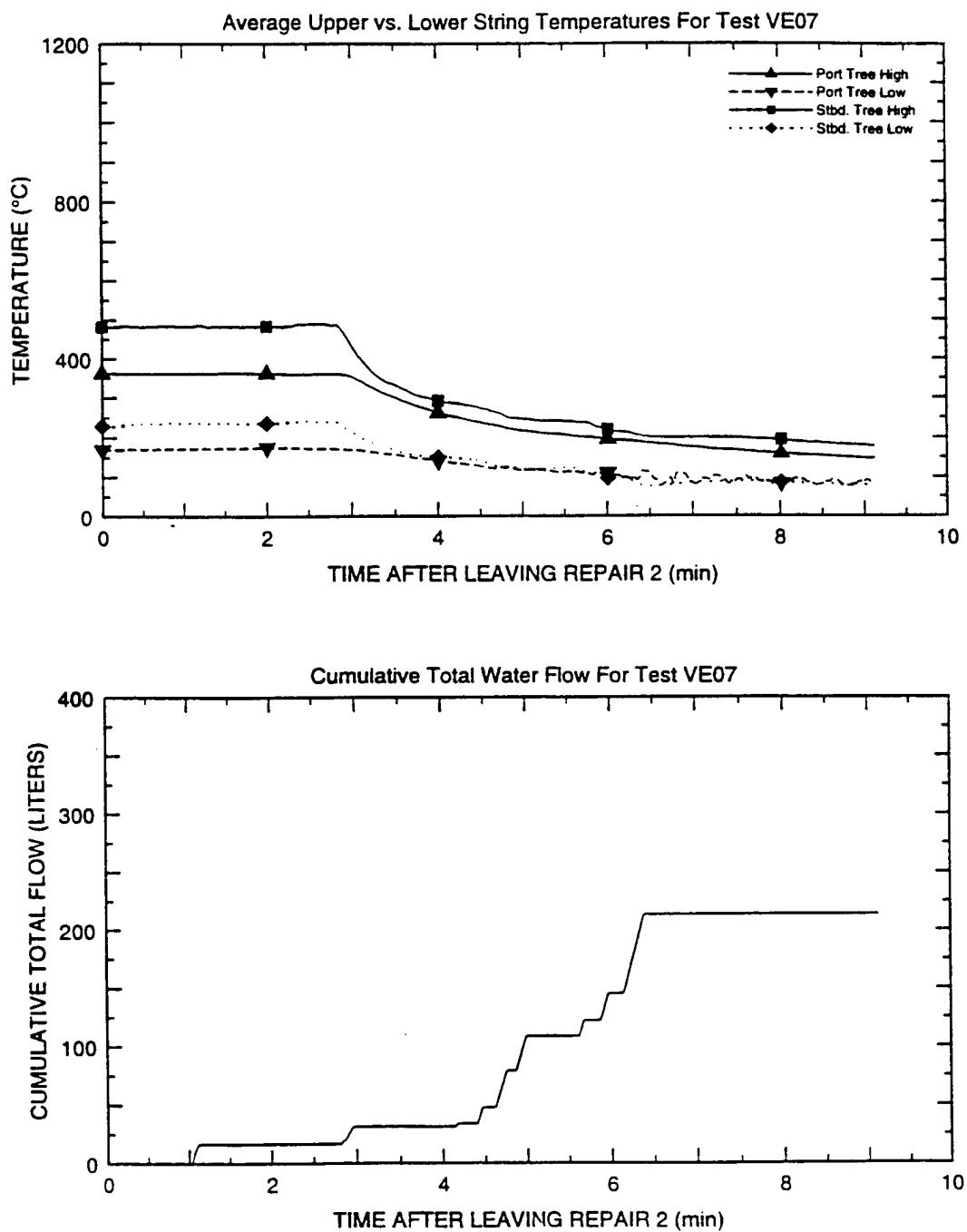


Fig. A14 — Average string temperatures and cumulative total water flow for test VE07

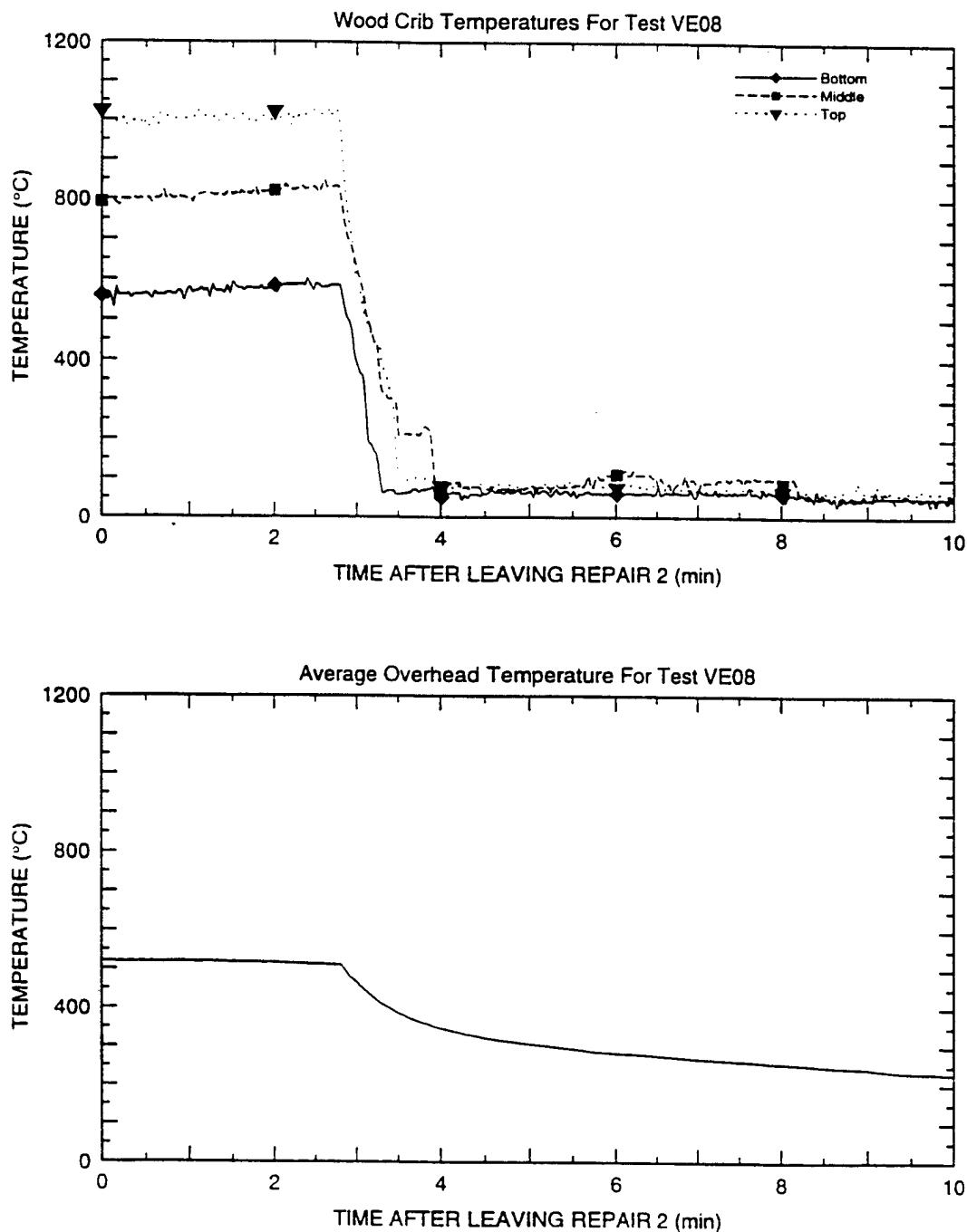


Fig. A15 — Wood crib and average overhead temperatures for test VE08

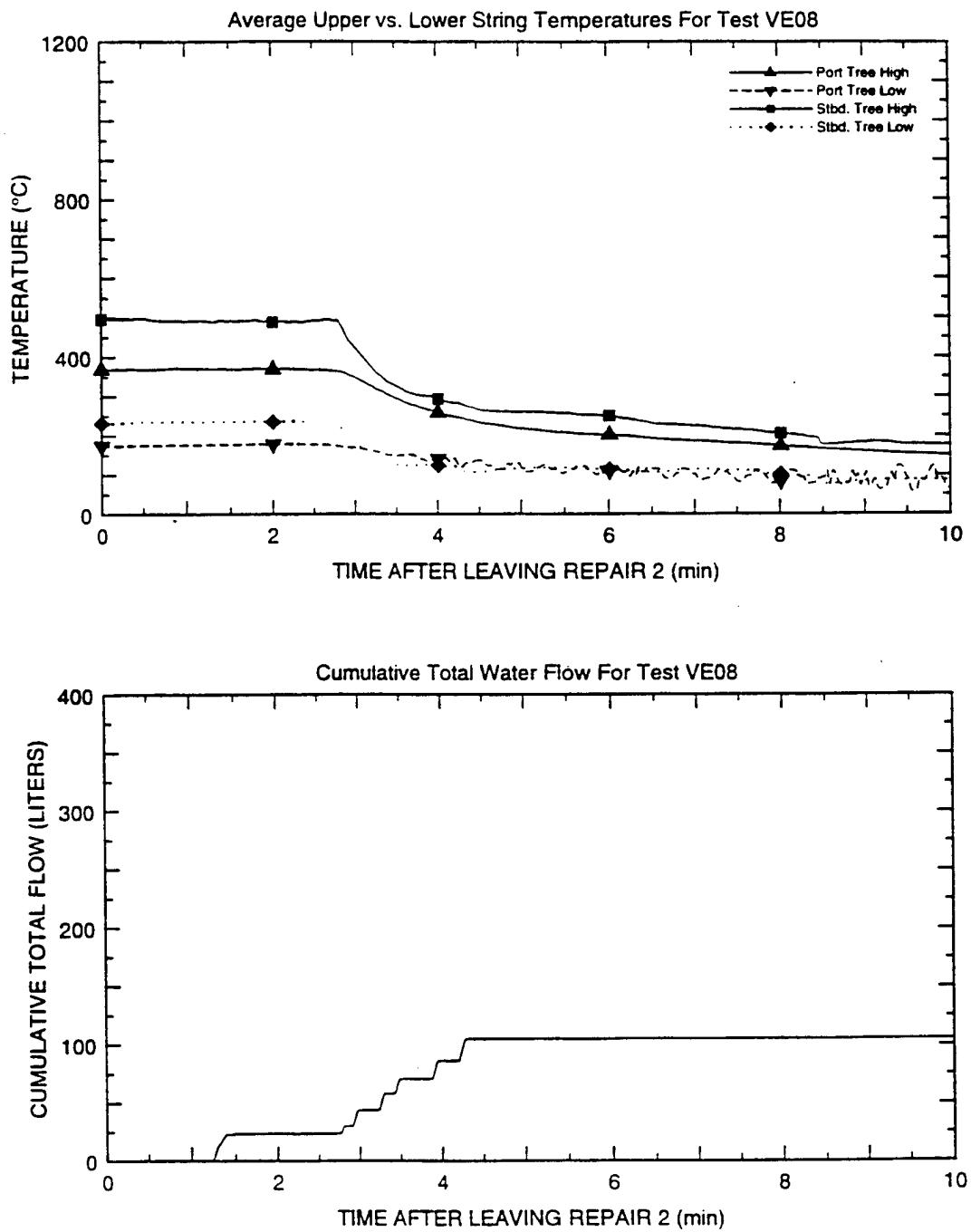


Fig. A16 — Average string temperatures and cumulative total water flow for test VE08

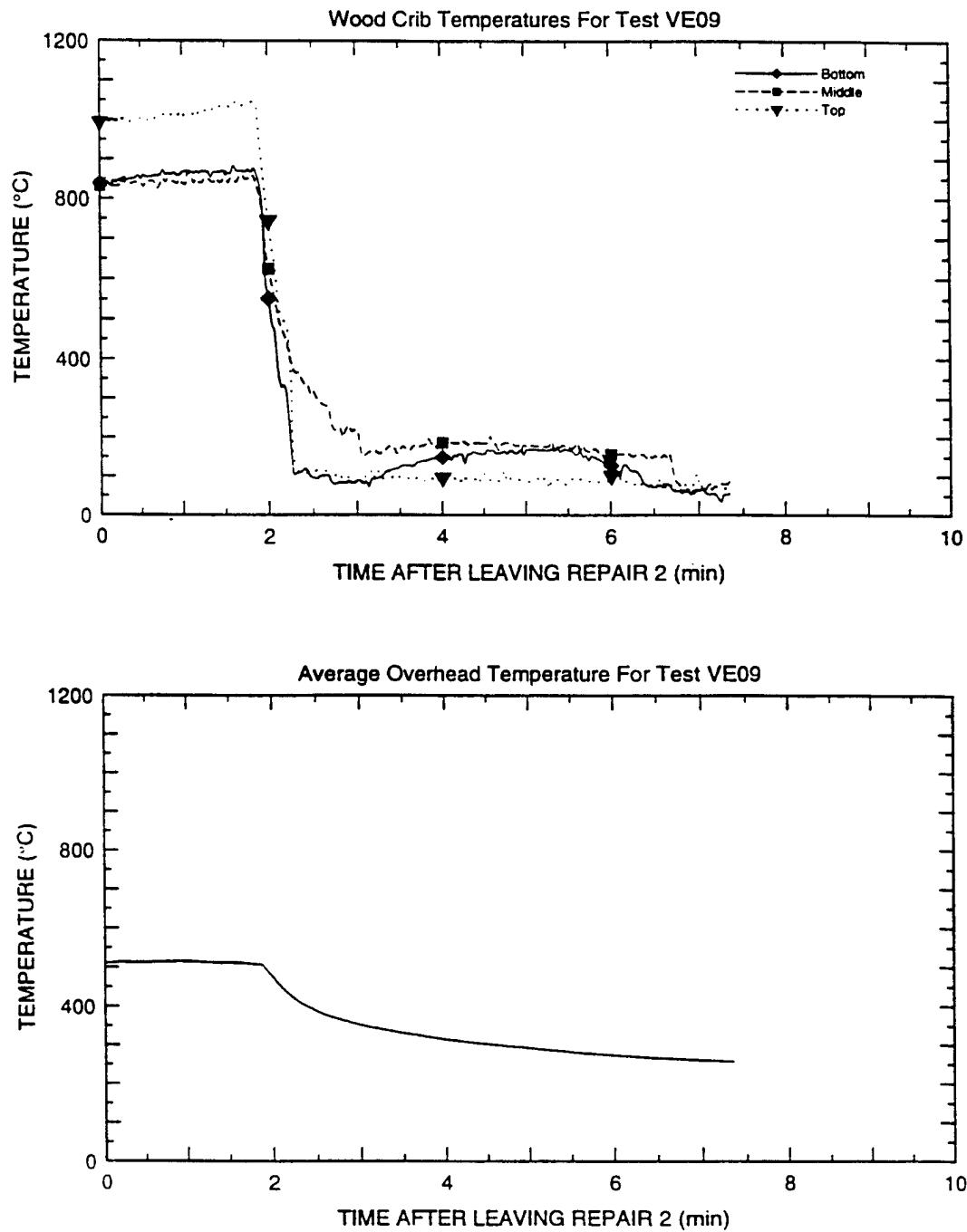


Fig. A17 — Wood crib and average overhead temperatures for test VE09

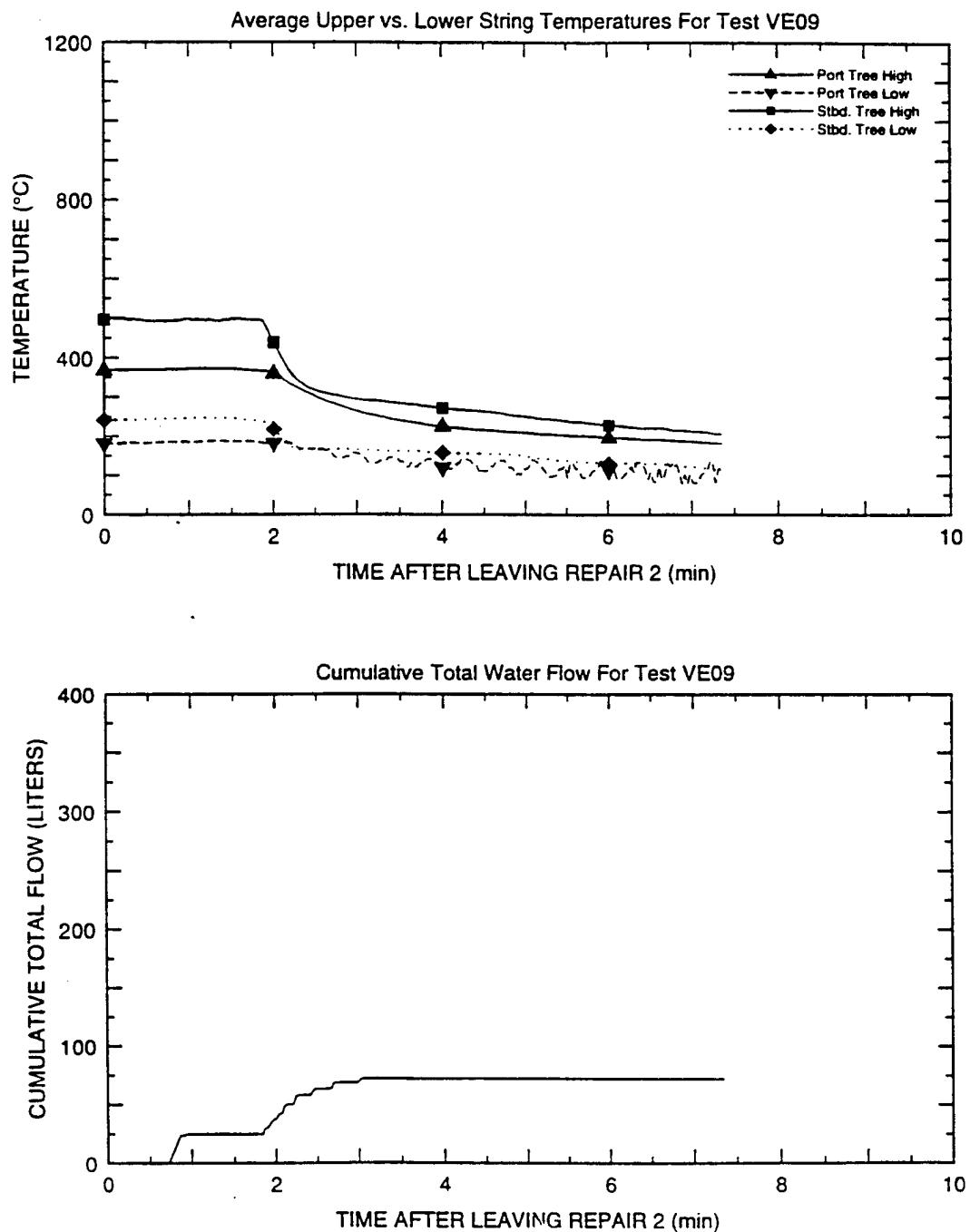


Fig. A18 — Average string temperatures and cumulative total water flow for test VE09

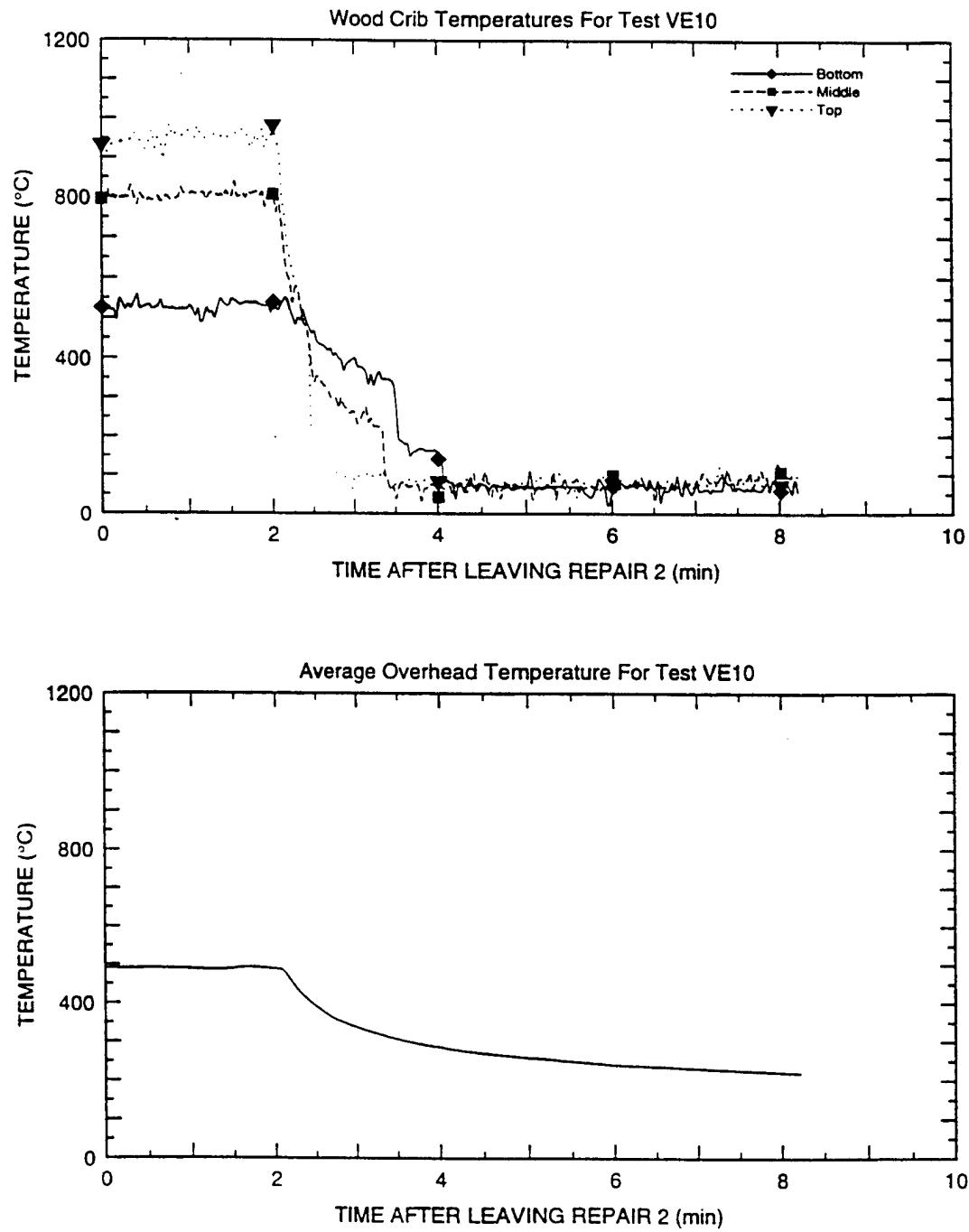


Fig. A19 — Wood crib and average overhead temperatures for test VE010

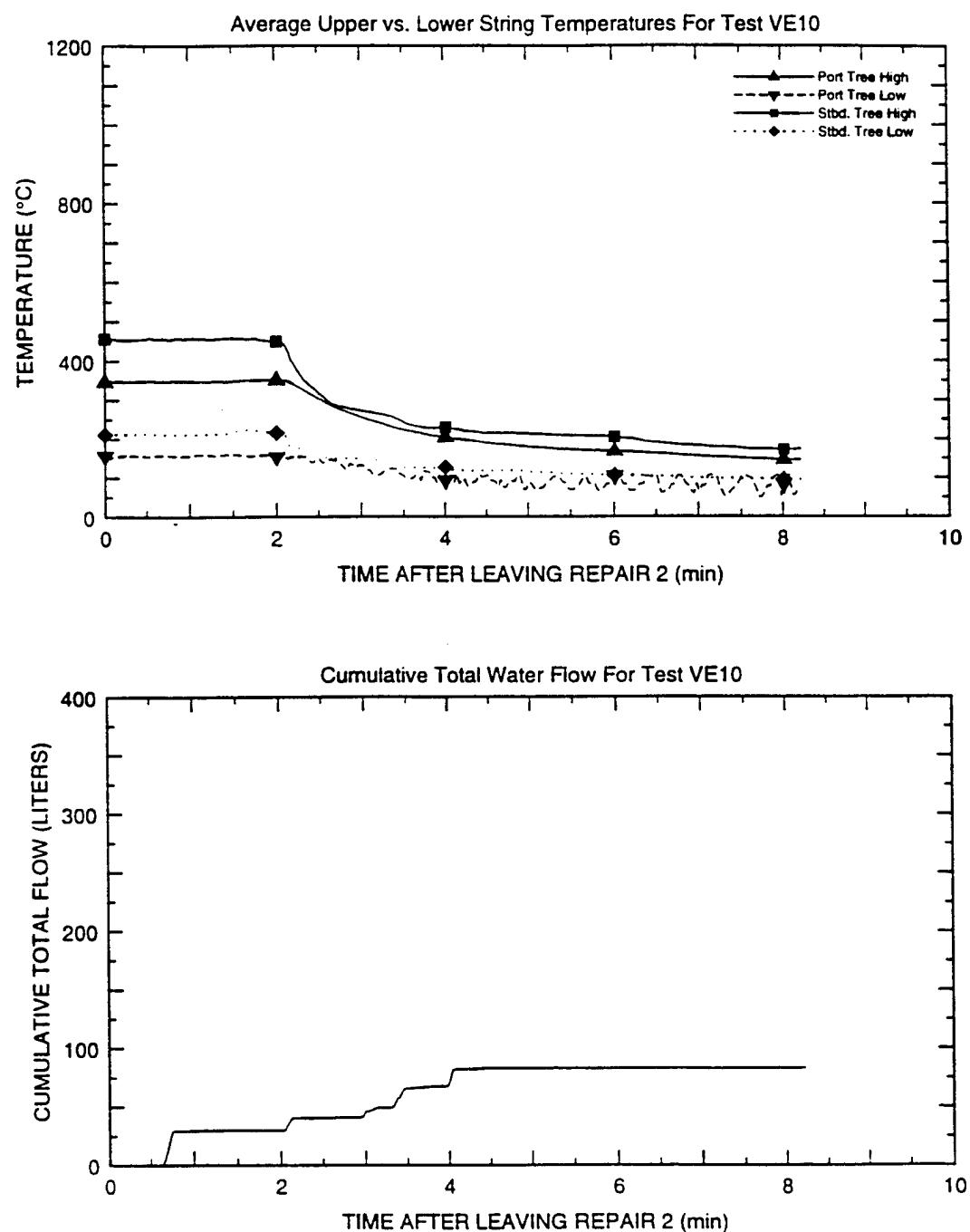


Fig. A20 — Average string temperatures and cumulative total water flow for test VE010

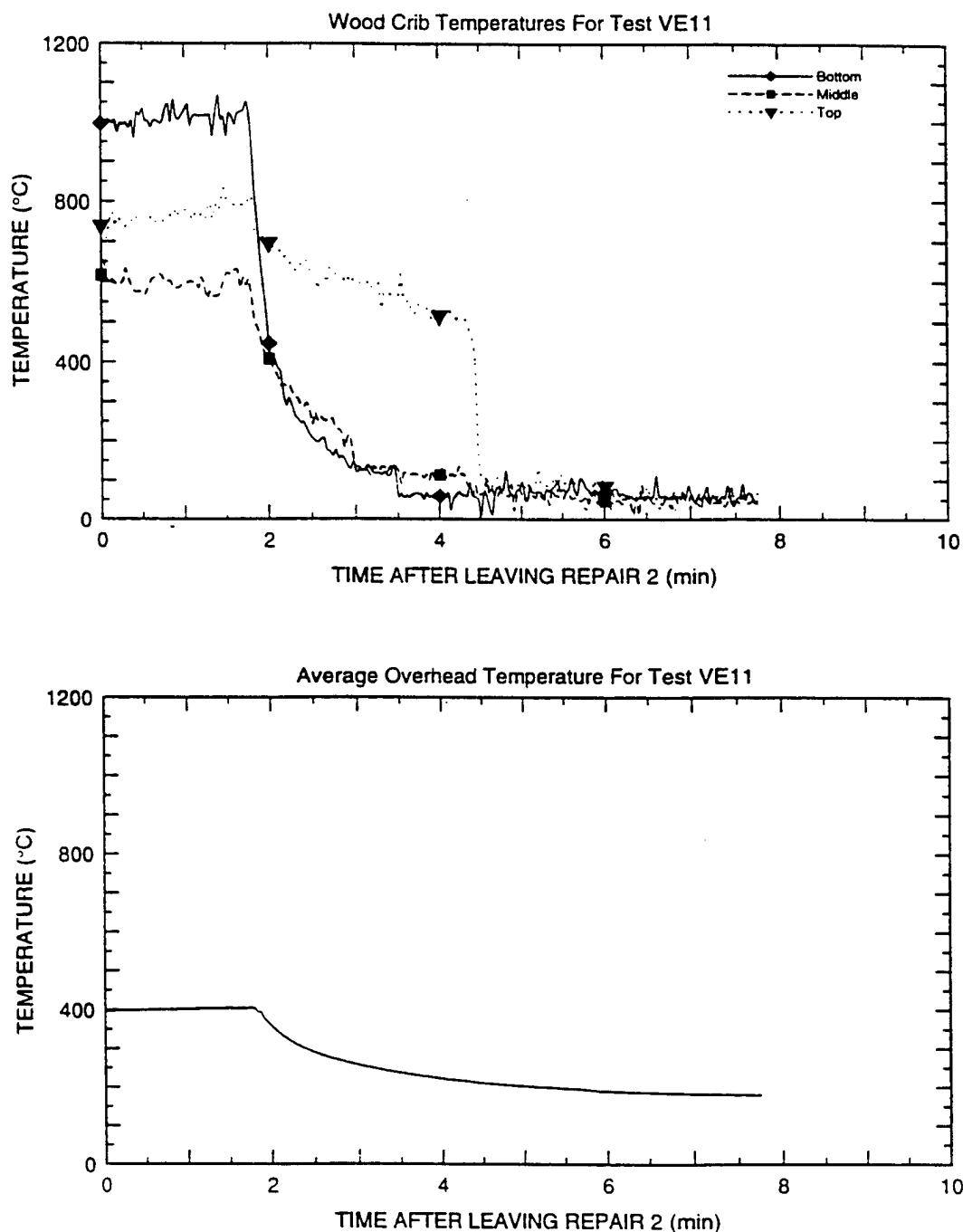


Fig. A21 — Wood crib and average overhead temperatures for test VE011

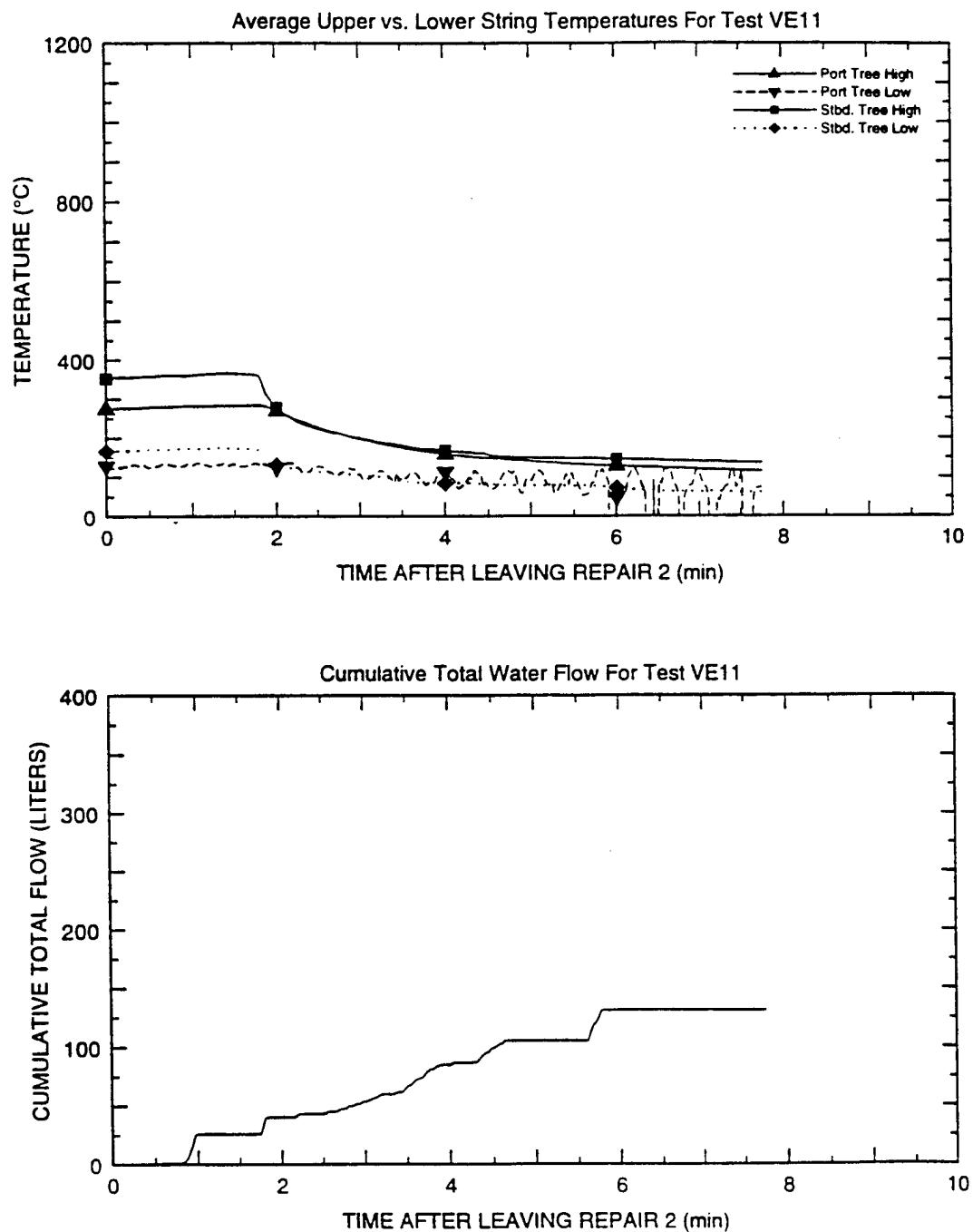


Fig. A22 — Average string temperatures and cumulative total water flow for test VE011

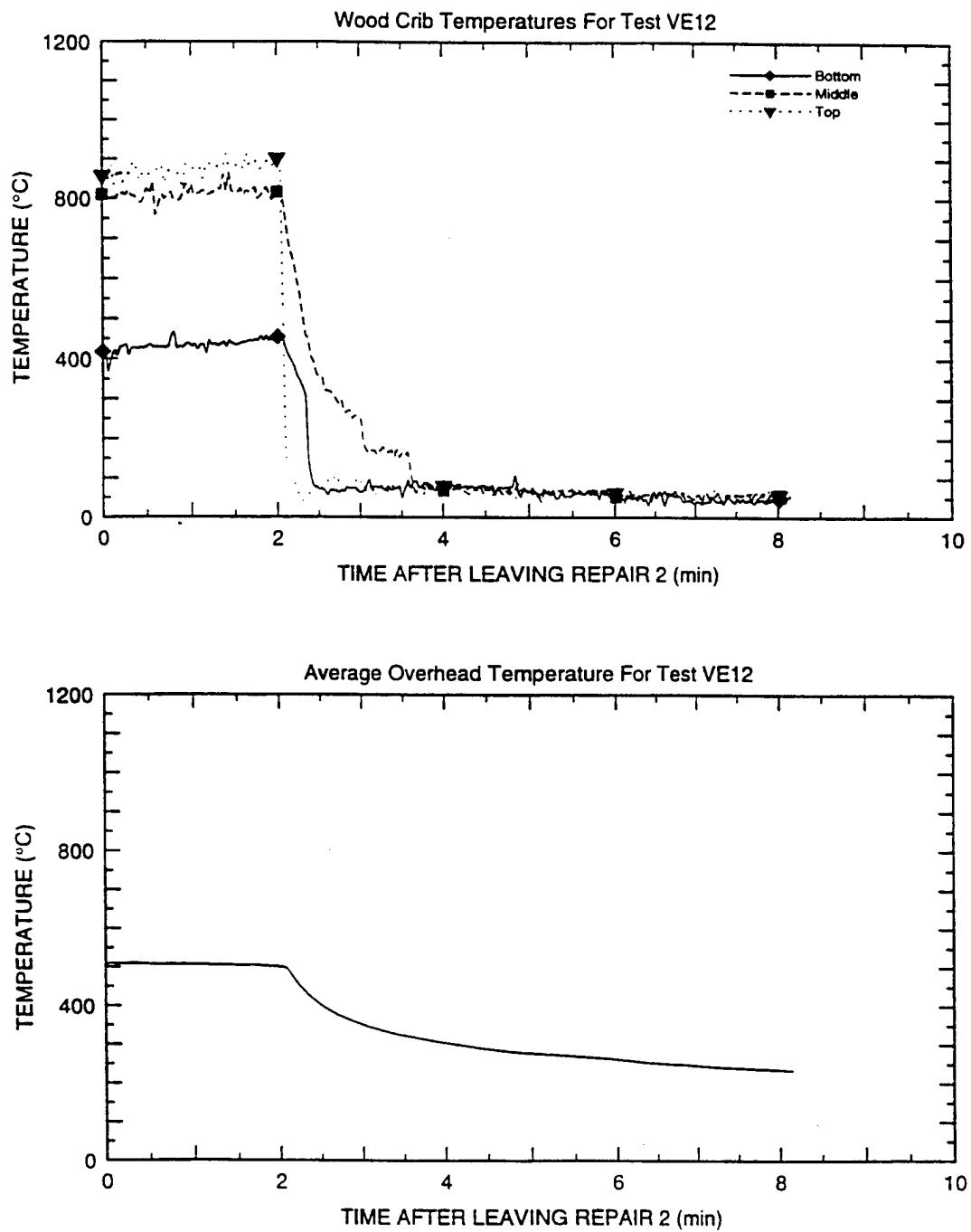


Fig. A23 — Wood crib and average overhead temperatures for test VE012

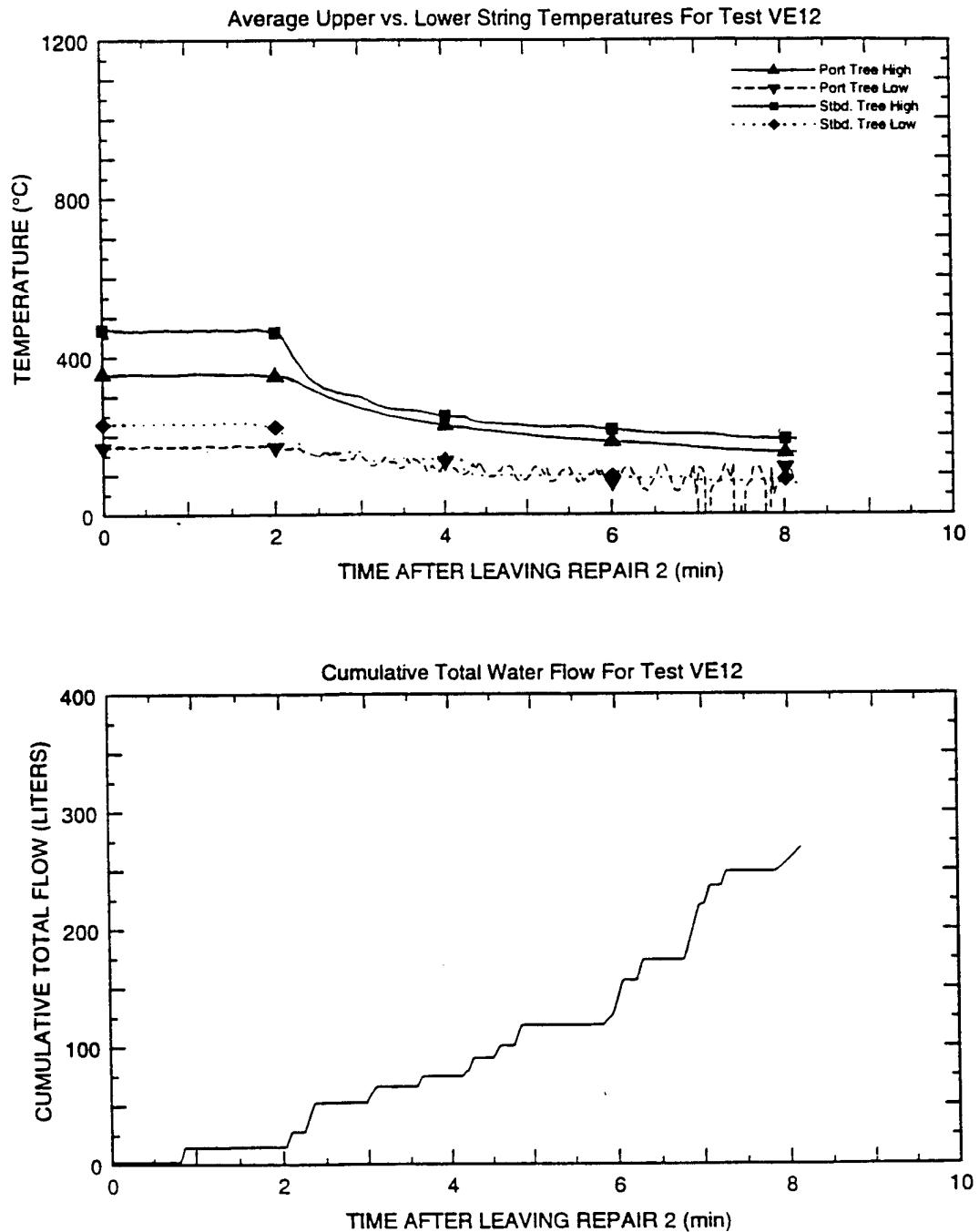


Fig. A24 — Average string temperatures and cumulative total water flow for test VE012